The Magnetic Field in the Outer Heliosphere

Steve Suess

NASA Marshall Space Flight Center /
National Space Science & Technology Center

1. Definition of 'the heliosphere'.

    Why the magnetic field in the outer heliosphere is interesting.

2. Very brief introduction to the solar wind and the interplanetary magnetic field.

    Steady state - Archimedian spiral in the solar wind and what this spiral looks like in the heliosheath.

    Transverse fluctuations in the polar heliosphere.

    Momentum exchange with newly ionized interstellar atoms.

3. The magnetic field in the heliosheath.

    - The "magnetic wall"

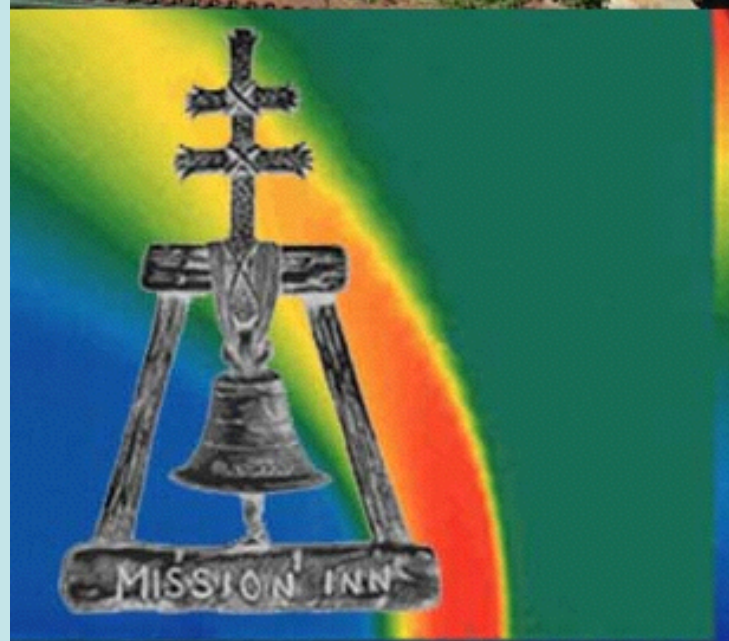4. Solar cycle imprint in the heliosheath.

The courtyard at the Mission Inn in California, where the meeting on Physics of the Outer Heliosphere was held.

The meeting room was to the right and the coffee breaks were held in the room on the left.

- The Sun continuously releases solar wind into the interplanetary medium.

- The solar wind fills the interplanetary medium and expands into the surrounding *'interstellar medium'*.

- The volume containing the solar wind is called *'the heliosphere'*.

COSMIC RAYS IN THE HELIOSPHERE (after Jokipii):

-a reason the outer heliosphere magnetic field is interesting.

The entry of cosmic rays into the heliosphere, and cosmic ray drifts in the heliosphere, depend on the magnetic field sign, strength, and structure.
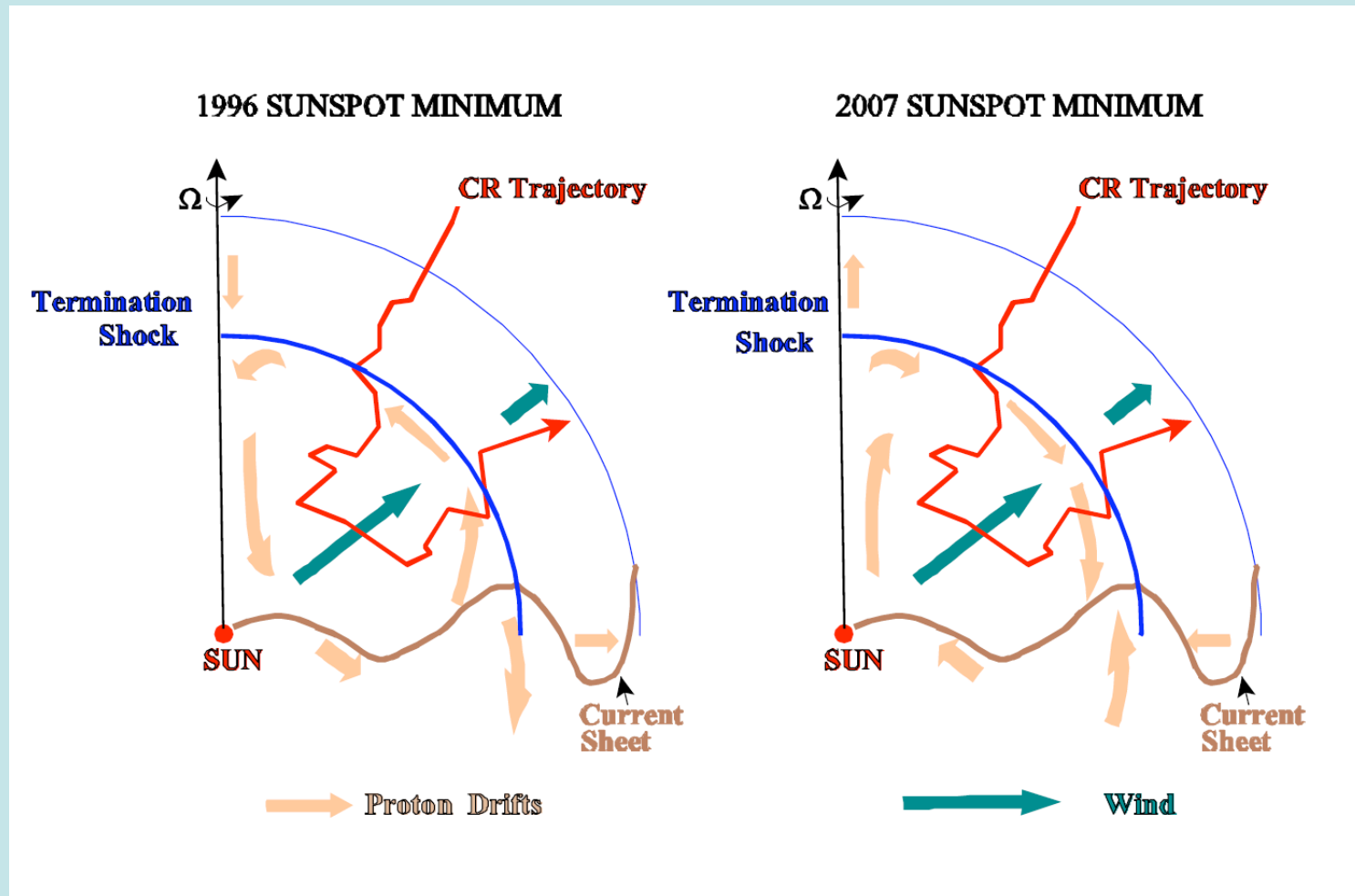
THE SOLAR WIND: a very brief introduction

The solar wind properties at 1 AU

$V_{SOLAR\ WIND} \sim$ 400 - 800 km/s, $\sim$ independent of distance to O[1]
   These speeds are reached by 10-50 R_{SUN}
   The solar wind is SUPERSONIC at 1 AU
   The solar wind, to O[1], DOES NOT COROTATE WTH
   THE SUN

Density $\sim$ 7 - 4 cm^{-3}, falling as r^{-2} to O[1]

Transit time to 1 AU $\sim$ 3.5 - 2.0 days

The interplanetary magnetic field (IMF) "Archimedian" spiral according to Parker:

As the solar wind expands, it carries along with it magnetic flux from the Sun.

The magnetic field is nearly passive.

Footpoints of the field lines are, more-or-less, attached to the Sun.

Therefore, as predicted by Parker (1963), the field lines are drawn into spirals by the 25.5 day rotation of the Sun (the "garden hose" effect).

Interplanetary Magnetic Field Spiral in Equatorial Plane & Near the Pole

Heliocentric Distance (AU)
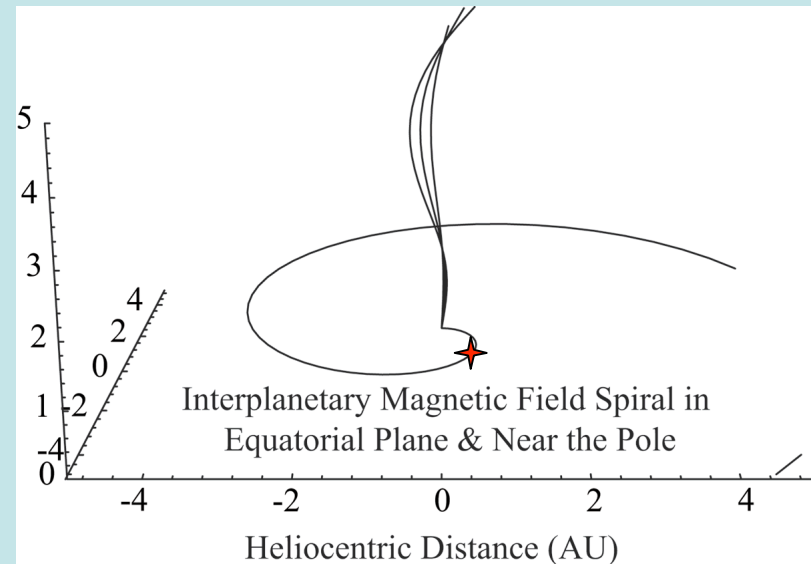
Since it takes 2 to 3.5 days for the solar wind to reach 1 AU, and 25.5 days for one revolution of the Sun, then a magnetic field line will be drawn into a spiral ~1/8th of revolution in length.

✦ This results in the spiral angle of the IMF at 1 AU being ~45º.

This prediction accurately describes the measured *average* IMF at 1 AU.

The interstellar medium is NOT EMPTY.

The solar wind blows into the "very local interstellar medium" (VLISM), causing a cavity (effectively an HII region).

This cavity is the HELIOSPHERE, defined as the volume out to the *contact discontinuity* between the solar wind and the VLISM.
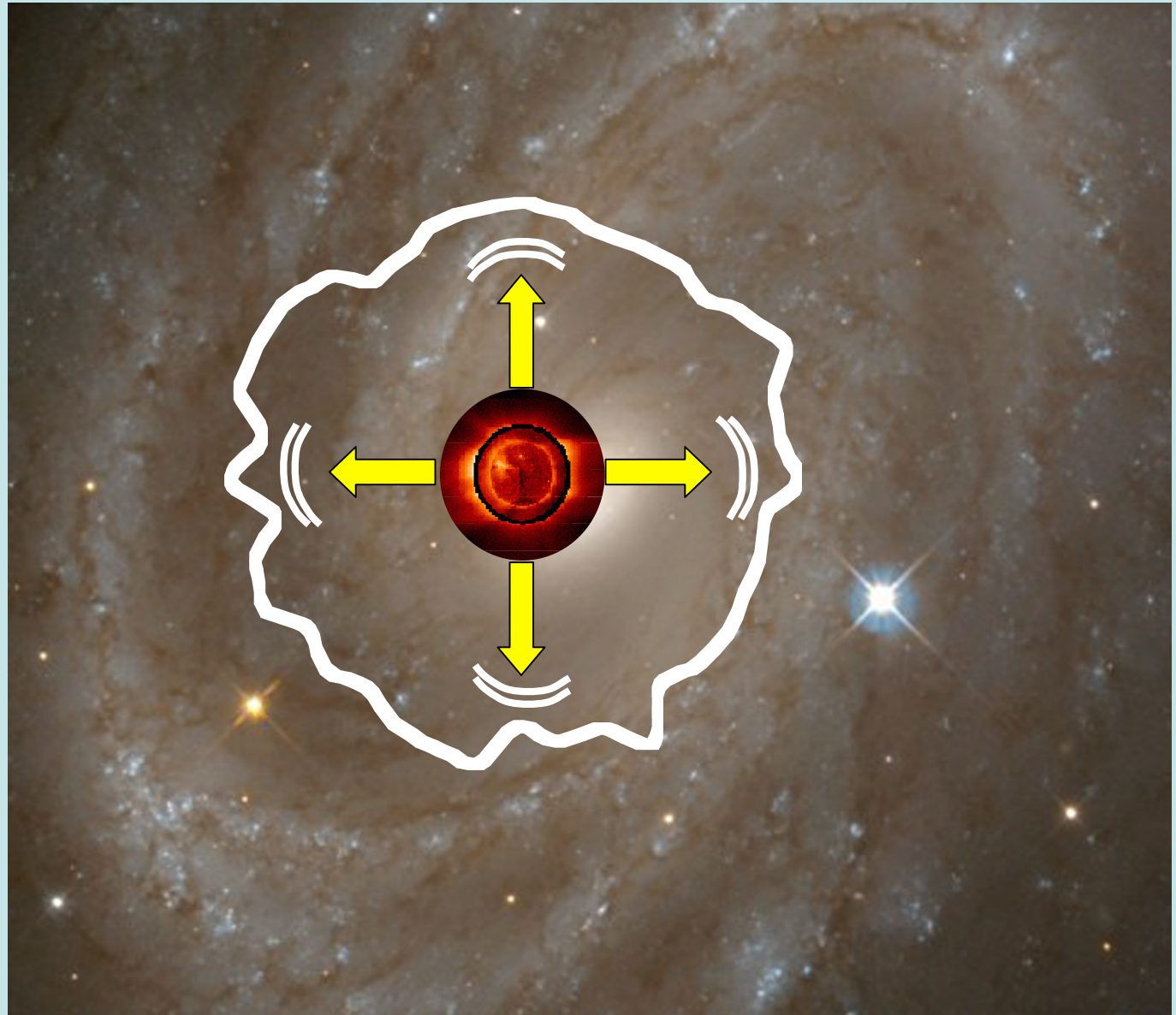
A BRIEF PHYSICAL EXPLANATION:

Parker considered the problem of a spherically symmetric wind expanding into a stationary surrounding medium.

1. Because the solar wind is supersonic, the back-pressure of the VLISM will eventually cause the solar wind to pass through a SHOCK TRANSITION to subsonic flow.

2. This is the TERMINATION SHOCK (TS).

3. <u>Beyond the TS</u>, the flow is ~incompressible and expanding into a spherical cavity.
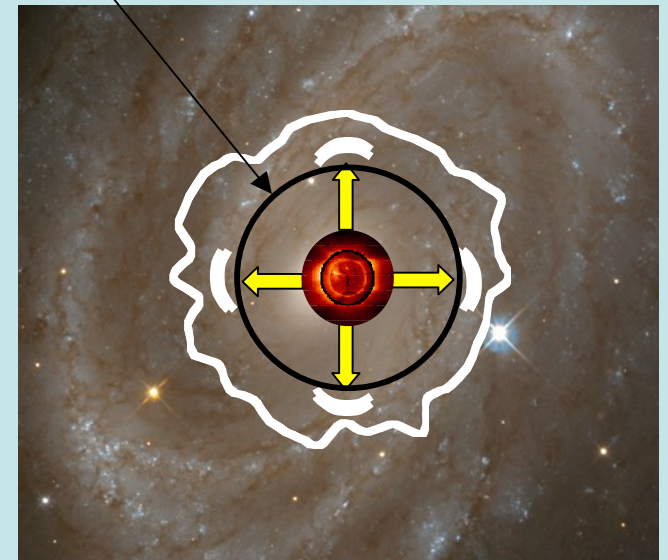
   Density ~ constant

   Flow speed $\propto r^{-2}$

   Pressure $\propto$ Density x Temperature ~ constant

4. Therefore, the cavity grows without bound, over time.

The pressure in the VLISM is ~ 10^{-12} dynes / cm^2

<u>The solar wind pressure only falls to this value at ~ 100 AU!</u>

This is the location of the TERMINATION SHOCK.

THE MAGNETIC FIELD AT THE TERMINATION SHOCK

It takes the solar wind ~ 1 YEAR to reach 100 AU.

$$\vec{B}_{IMF} \approx B_{\phi o}\hat{e}_\phi \frac{r_o}{r} + B_{ro}\hat{e}_r\left(\frac{r_o}{r}\right)^2 ; \qquad \frac{B_\phi}{B_r} \propto r$$
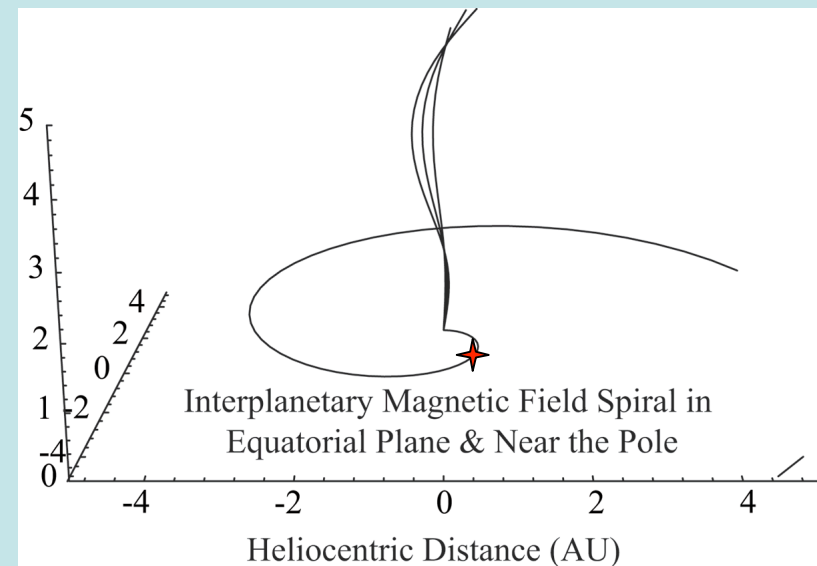
Therefore,

The spiral angle at the Termination Shock is ~ 90°

(compared to ~45° at 1 AU)

In other words, the magnetic field is ~ parallel to the surface of the termination shock.

$$\vec{B}_{IMF} \approx B_\phi \hat{e}_\phi \qquad \text{at 100 AU}$$

In this case, the termination shock is a "perpendicular shock".

Interplanetary Magnetic Field Spiral in Equatorial Plane & Near the Pole

Heliocentric Distance (AU)

Adding a magnetic field to the previous problem of a wind expanding into a spherical cavity beyond the Termination Shock changes things.

Consider the IMF as if it were still passive.

The flow speed $\propto r^{-2}$.

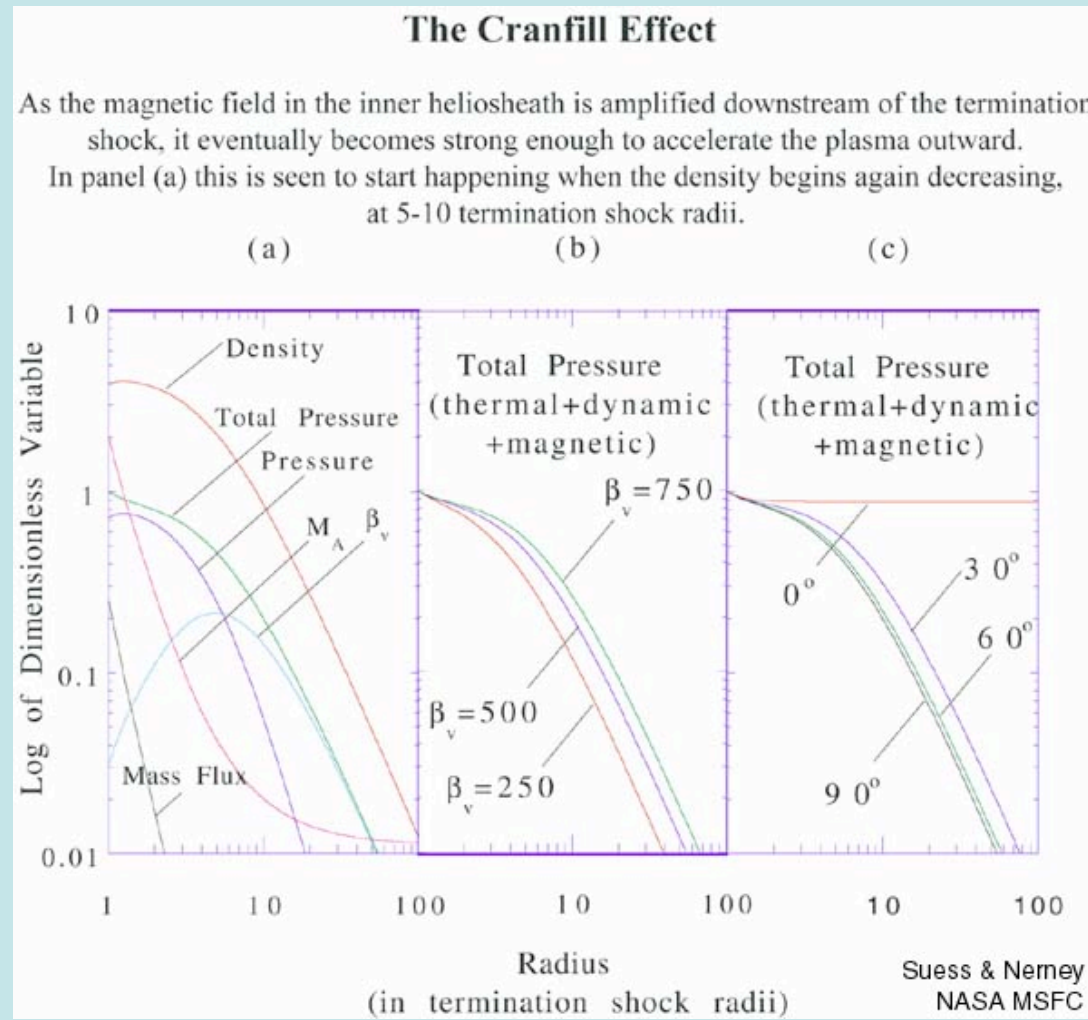The field is ~ transverse to the spherically expanding flow.

<u>Therefore, beyond the termination shock,</u>

$$\vec{B}_{IMF} \approx B_{TS}\hat{e}_{\phi} \frac{r}{r_{TS}} \propto r$$

The magnetic field strength is <u>increasing</u> with distance because the flow speed is decreasing and the field is transverse to the flow direction.

Eventually, the magnetic field strength becomes large enough to effectively push outwards on the VLISM.

This slows the deceleration of the flow, something known as the "Axford-Cranfill effect".

The Cranfill Effect

As the magnetic field in the inner heliosheath is amplified downstream of the termination shock, it eventually becomes strong enough to accelerate the plasma outward. In panel (a) this is seen to start happening when the density begins again decreasing, at 5-10 termination shock radii.
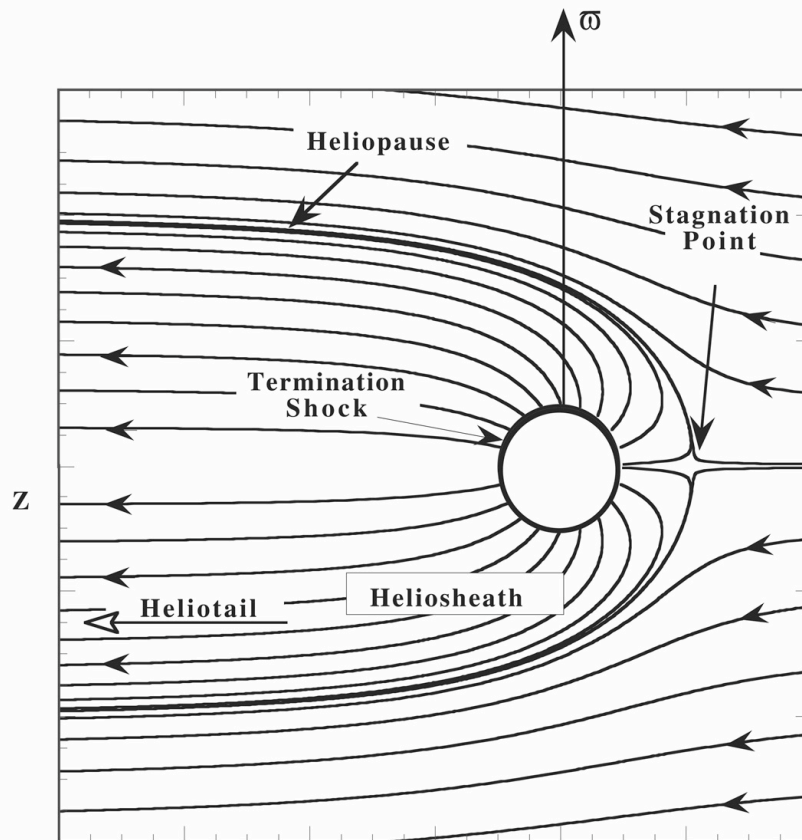
Suess & Nerney
NASA MSFC

Nerney, Suess, & Schmahl, *A&A, 1991.*

But, the solar system is MOVING (supersonically, at ~25 km/s) THROUGH THE VLISM.
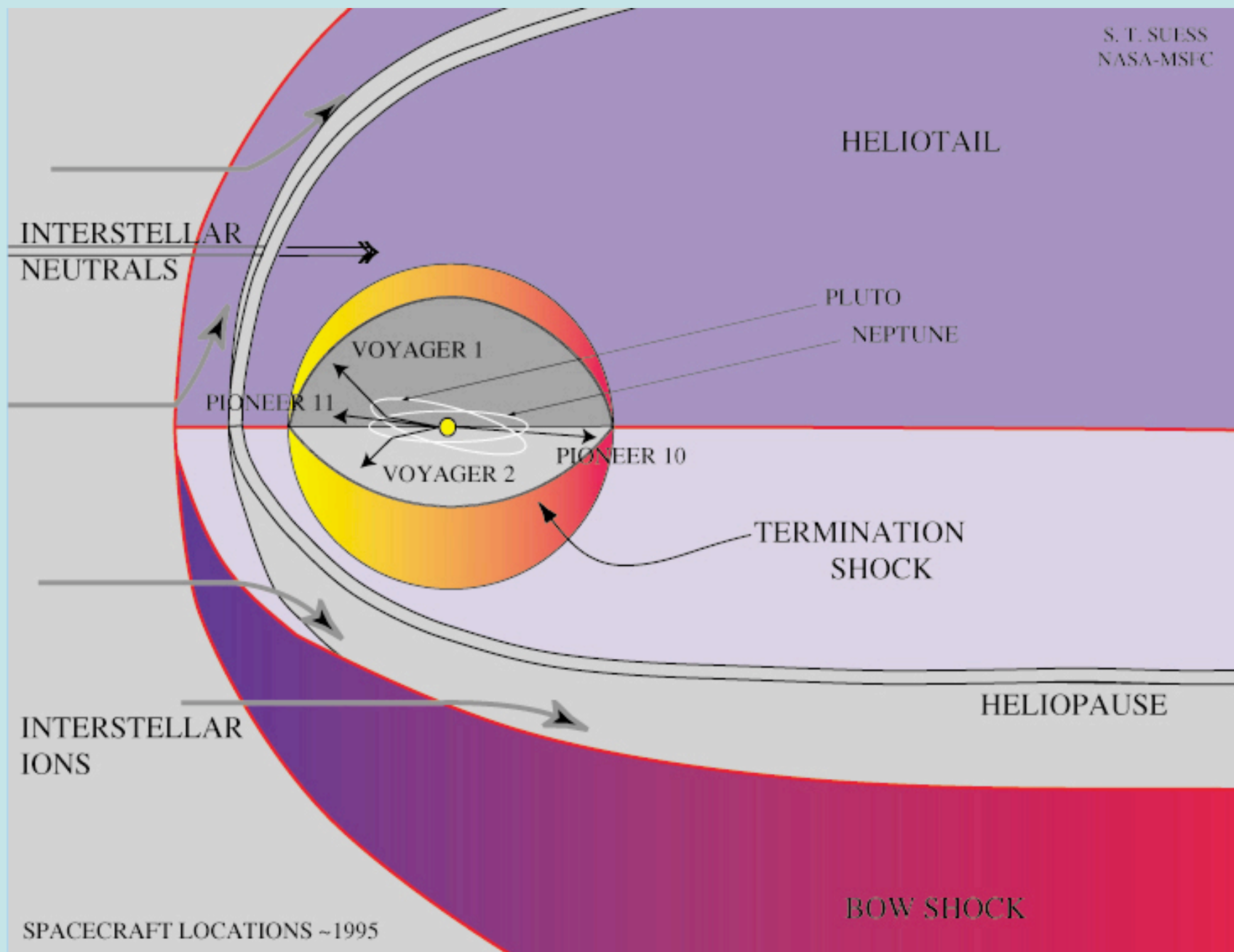
This causes the heliosphere to form:

(a)   An upstream bowshock

(b)   A downstream heliotail

(c)   **And form a shape something like that of the Earth's magnetosphere.**
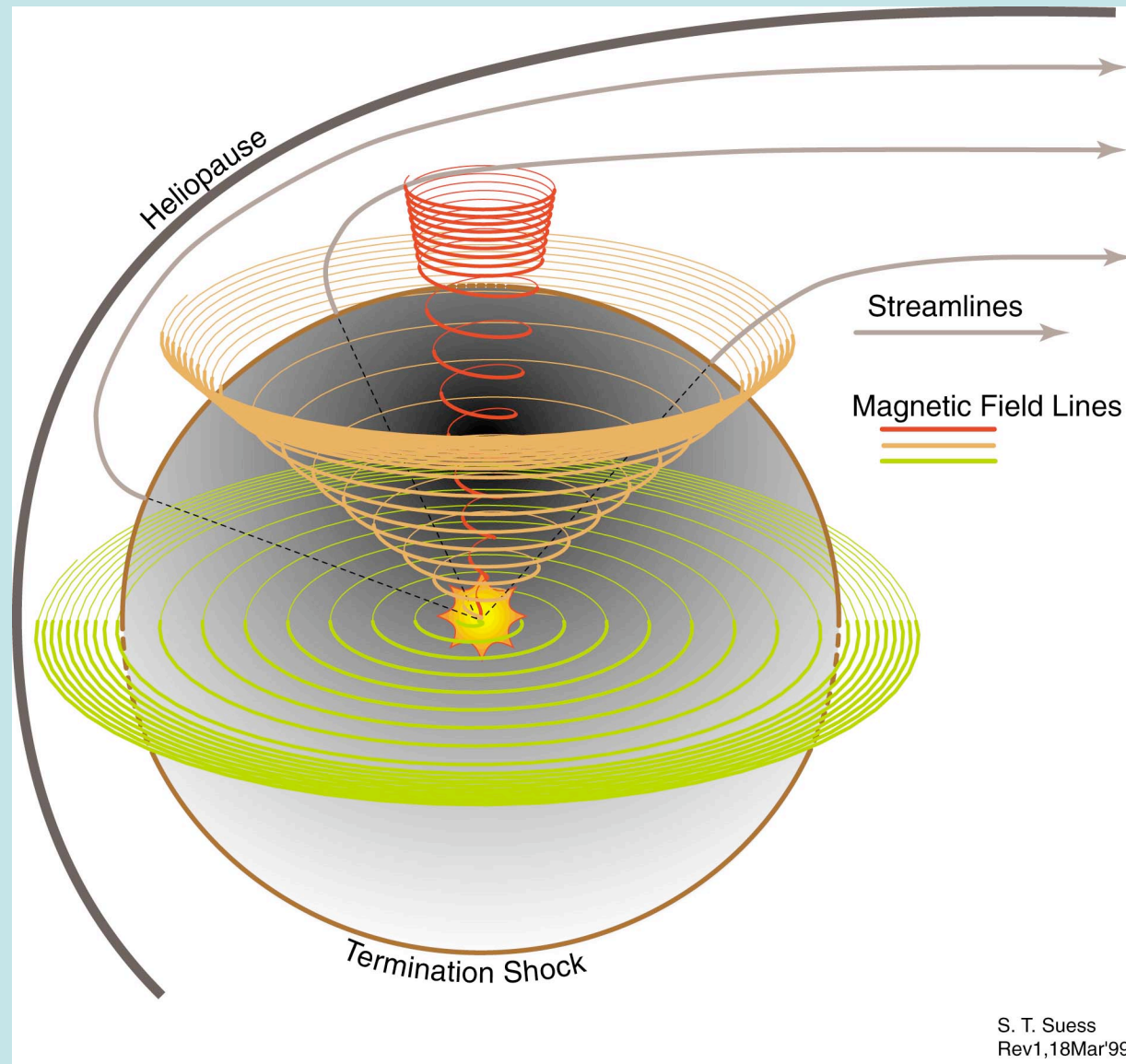

What you see at the left is a solution for irrotational & incompressible flow in the "heliosheath" and the VLISM (Suess & Nerney, 1991), an extension of a model described by Parker (1963).
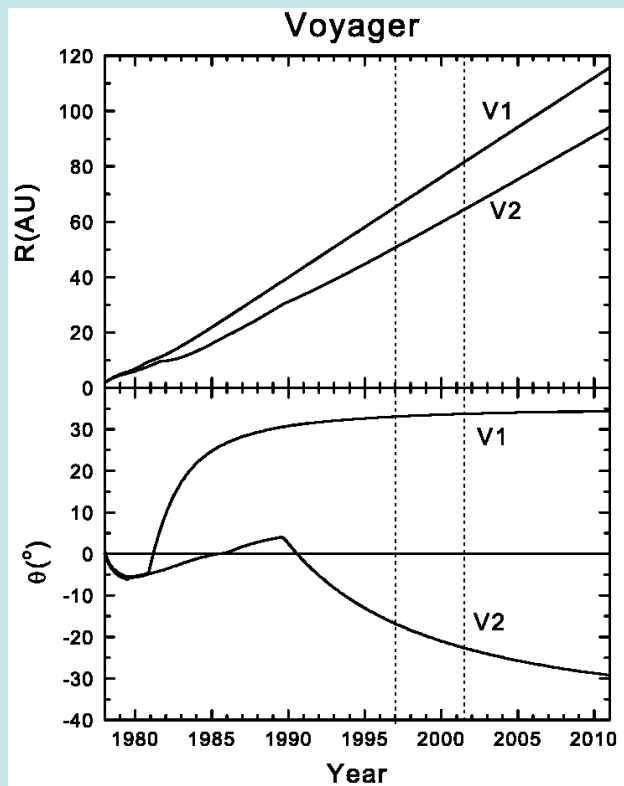
Because of the motion through the VLISM, the Axford-Cranfill effect is of little importance in the heliosheath.
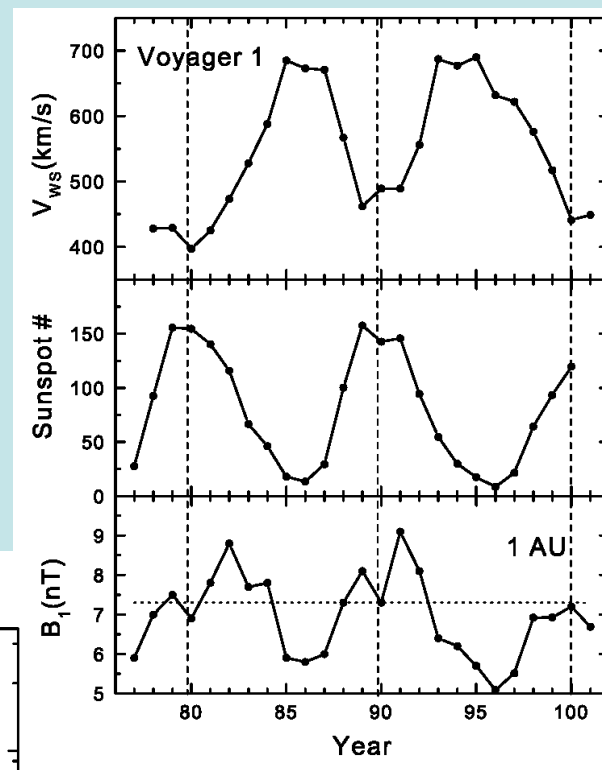
HELIOTAIL

INTERSTELLAR
NEUTRALS

PLUTO

NEPTUNE

VOYAGER 1

PIONEER 11

VOYAGER 2

PIONEER 10

TERMINATION
SHOCK

HELIOPAUSE

INTERSTELLAR
IONS

SPACECRAFT LOCATIONS ~1995

BOW SHOCK

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Finally, the scene is set for a description of the magnetic field in the outer heliosphere.

Heliopause

Streamlines

Magnetic Field Lines

Termination Shock

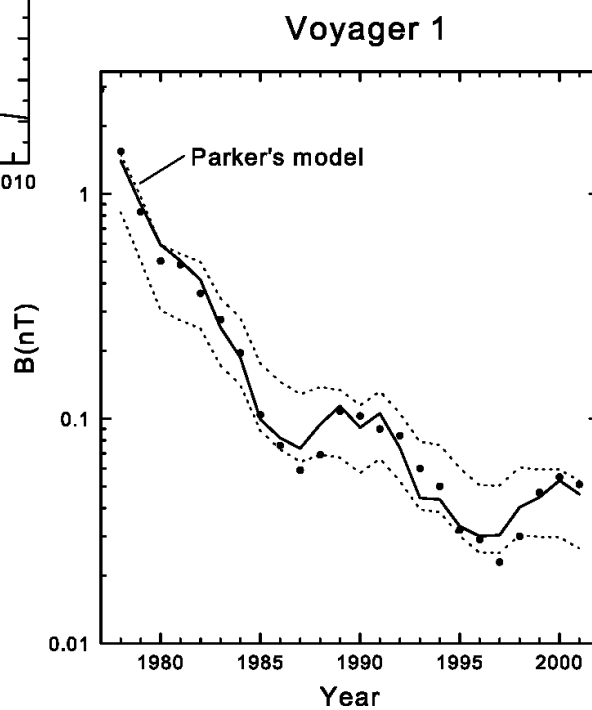S. T. Suess
Rev1,18Mar'99

Voyager

Voyager 1

+

=

Burlaga, Ness, Wang, & Sheeley, Heliospheric magnetic field strength & polarity from 1 to 81 AU during the ascending phase of solar cycle 23, *JGR*, *107(A11)*, 2002.

Slowing of the distant solar wind by charge exchange, and hence momentum exchange, with inflowing interstellar neutral atoms:
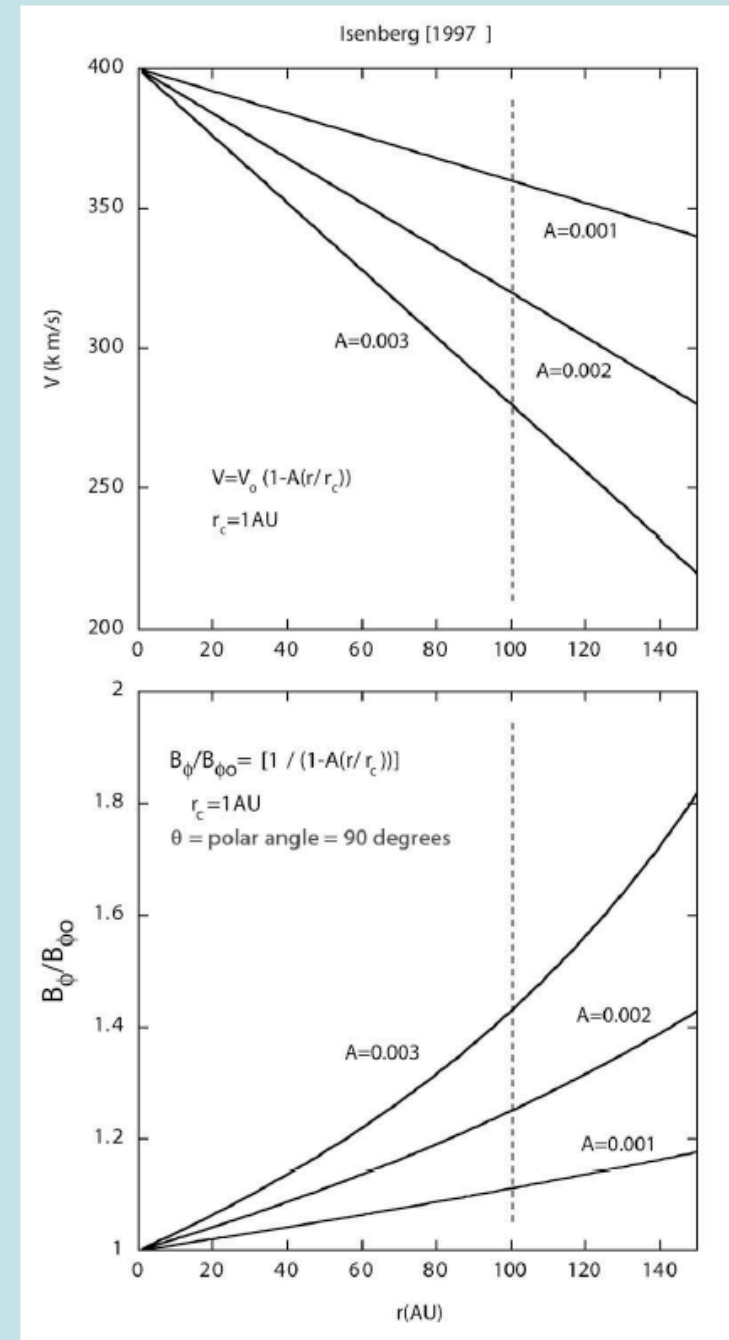
The solar wind speed falls off with distance due to momentum exchange of the solar wind through charge exchange with incoming (~25 km/s) interstellar neutral atoms. Isenberg derives an approximation for this slowing:

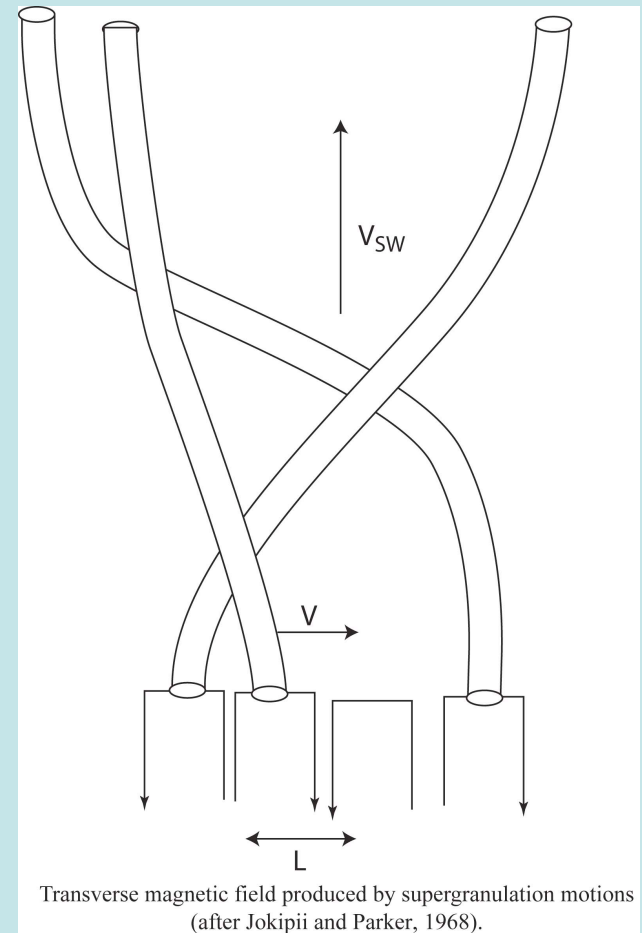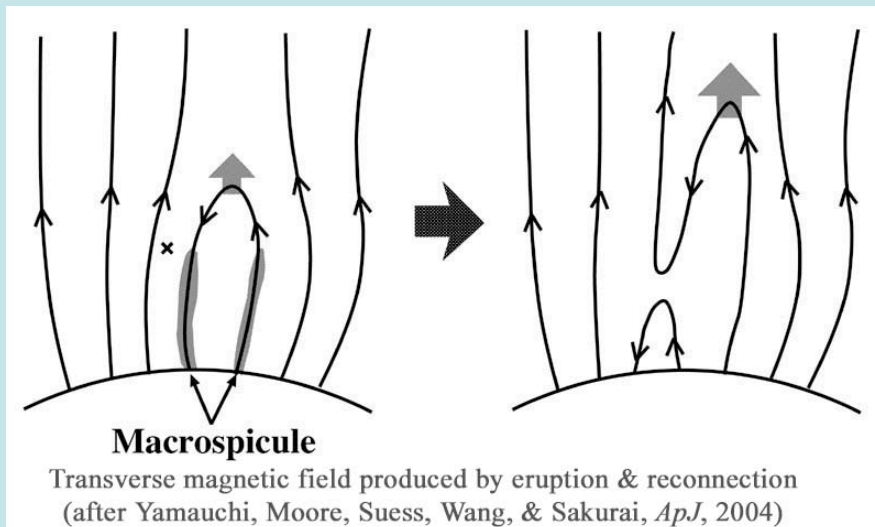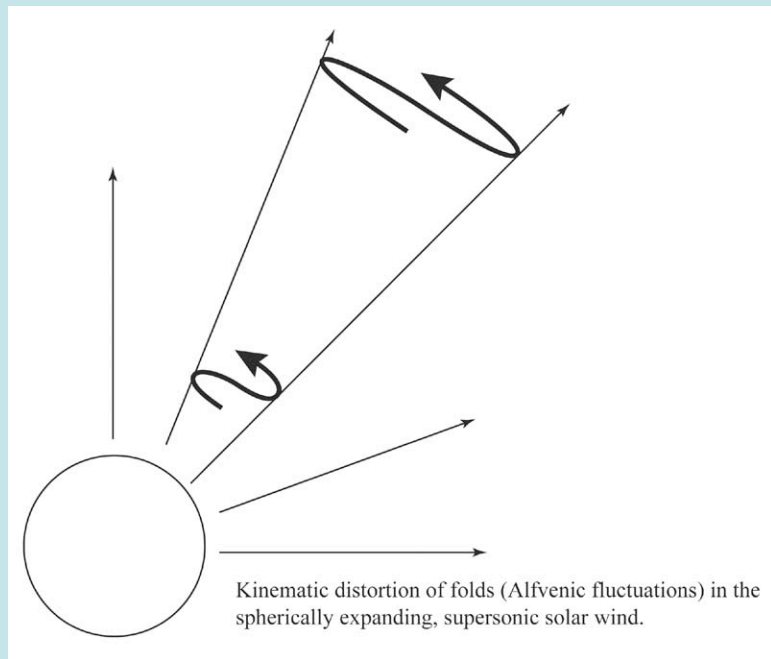$$V \approx V_o\left(1 - A\frac{r}{r_E}\right), \qquad r_E = 1AU$$

Solar wind speed falls linearly with distance in this approximation. This increases the azimuthal magnetic field (B_ϕ), as shown in the bottom panel.

For a 20% speed reduction at 100 AU (A=0.002), the spiral field strength is increased by 25%.
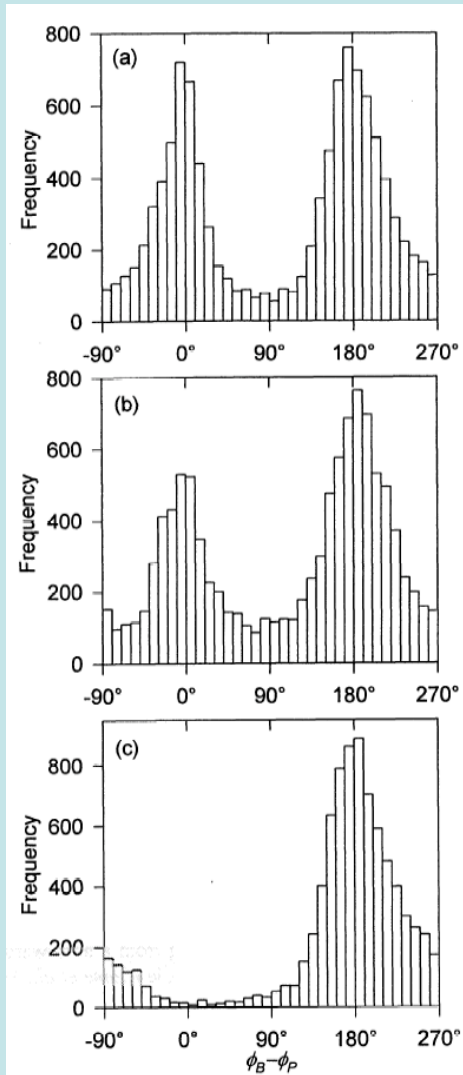
[Isenberg, P. A., A weaker solar wind termination shock, *GRL, 24(6)*, 623-626, 1997; *op. cit*]

Isenberg [1997]

Transverse fluctuations in the magnetic field:

Kinematic distortion of folds (Alfvenic fluctuations) in the spherically expanding, supersonic solar wind.

V_{SW}

V

L

Transverse magnetic field produced by supergranulation motions (after Jokipii and Parker, 1968).

Macrospicule
Transverse magnetic field produced by eruption & reconnection (after Yamauchi, Moore, Suess, Wang, & Sakurai, *ApJ*, 2004)
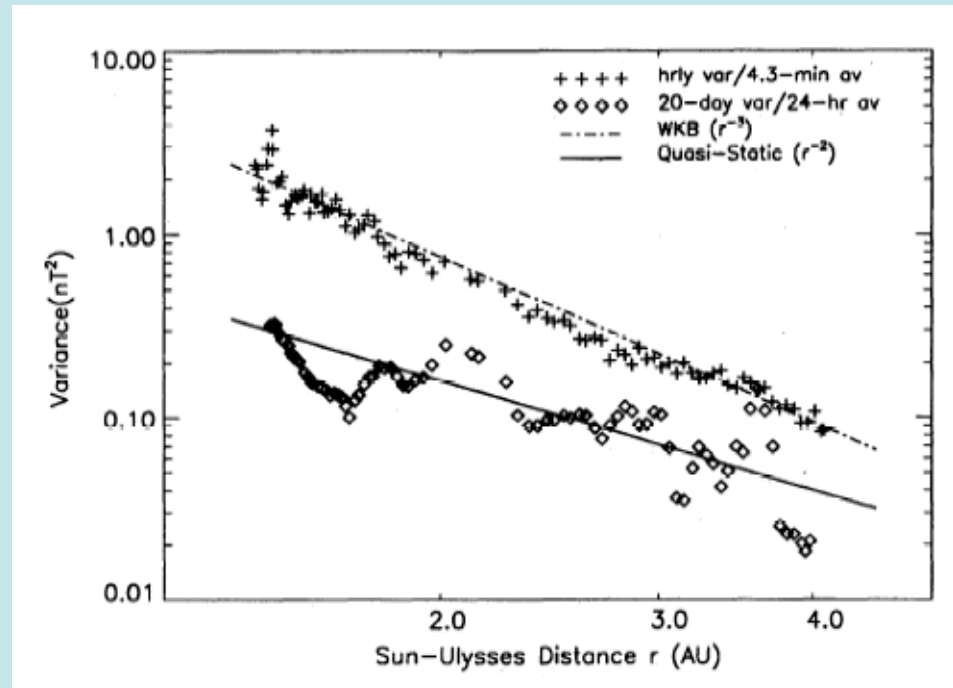
Jokipii, J. R., & J. Kóta, *GRL*, 1989.

Histograms of the deviation in azimuth angle, $\phi_B - \phi_B$, from the expected Parker model magnetic field direction binned into 10° intervals for (a) the in-ecliptic cruise phase of the Ulysses mission, (b) the out-of-ecliptic phase for heliographic latitudes between 6ºS and 30ºS, and (c) latitudes between 30ºS and 60ºS.

[Forsyth, et al*., JGR, 101(A1)*, 395-403, 1996]

Comparison of observed variances of the ***transverse magnetic field and model predictions***. Data points, in 1º latitude bins, are indicated by the symbol (+) corresponding to hourly variances of 4.3 min. avg. transverse magnetic field. The dash-dot curve is the unnormalized WKB prediction and the solid line is the quasi-static prediction, with the normalizatoin set by supergranulation parameters.

[Jokipii, J. R., J. Kóta, J. Giacalone, T. S. Horbury, and E. J. Smith, Interpretation and consequences of large-scale magnetic variances observed at high heliographic latitude, GRL, 22(23), 3385-3388, 1995.
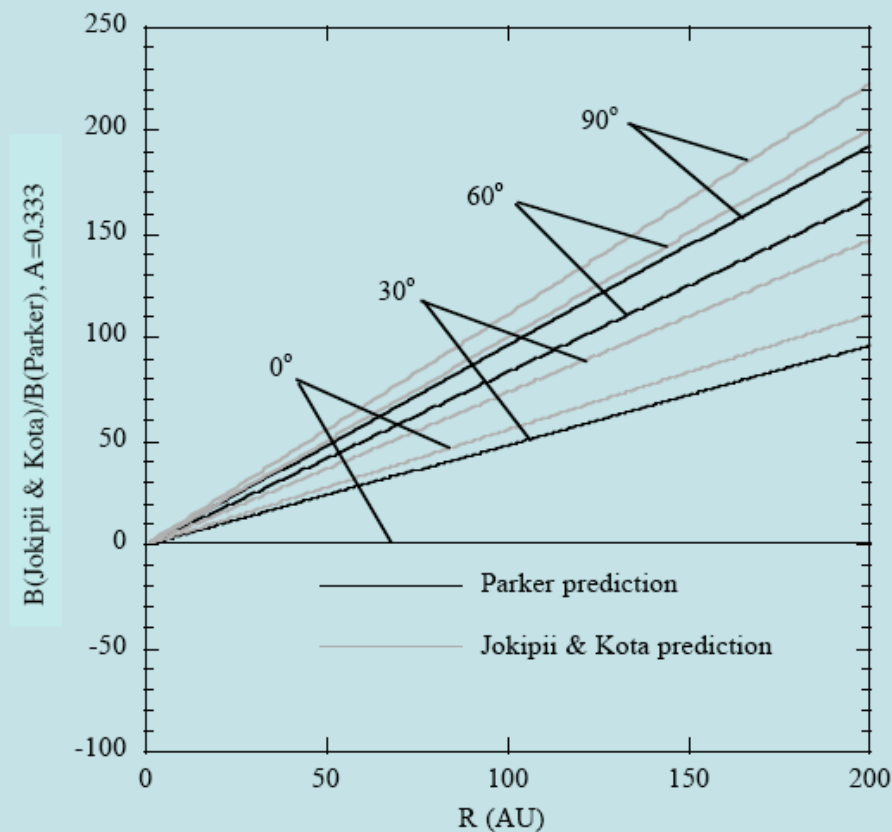
How the field varies with distance according to Jokipii and Kota:

- The *average* spiral angle is unchanged by the presence of the transverse fluctuations.

- The *average* magnetic field strength falls off more slowly with distance than in the Parker spiral.

•**The is the main source of scattering of cosmic rays at high heliographic latitudes.**

For example, on the right is a case in which B(Jokipii&Kóta) is ~16% larger than B(Parker) in the equator. This leads to a much larger relative increase at the poles because B(J&K) falls off only as 1/r and is independent of polar angle.

(The angles on the right are polar angles)

(This example is for kinetic fluctuations - WKB fluctuations would have a smaller effect)

250

200

150

100

50

0

-50

-100

B(Jokipii & Kota)/B(Parker), A=0.333

90°

60°

30°

0°

——— Parker prediction

——— Jokipii & Kota prediction

0   50   100   150   200

R (AU)

A caution:

As shown by Jokipii, Giacalone, Kóta, and more recently by Fisk and his colleagues, the movement of field line footpoints on the Sun muddies the nice picture of Archimedian spirals.
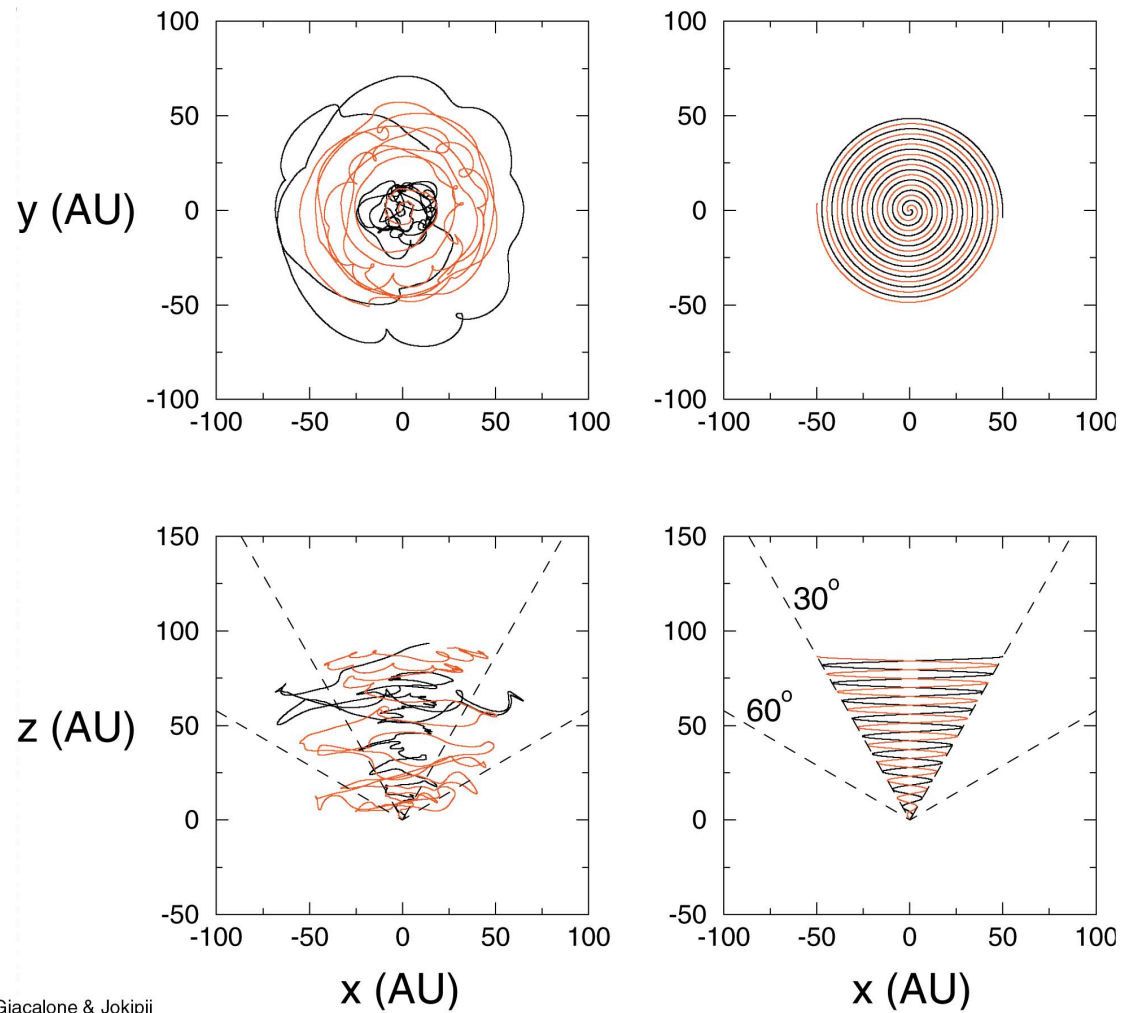

Giacalone & Jokipii
April 1999

STEPPING BACK, NOW, TO THE *IDEAL* MAGNETIC FIELD

Modeling the magnetic field in the heliosheath (using the analytic model):

<u>Flow field</u>: The simple potential (incompressible) flow model of Parker, as generalized by Suess & Nerney. The shock is spherical, the model is axisymmetric about the heliotail, and there is no bow shock or magnetic field.

<u>Magnetic field</u>: the magnetic field is put in passively - a 'kinematic' magnetic field.
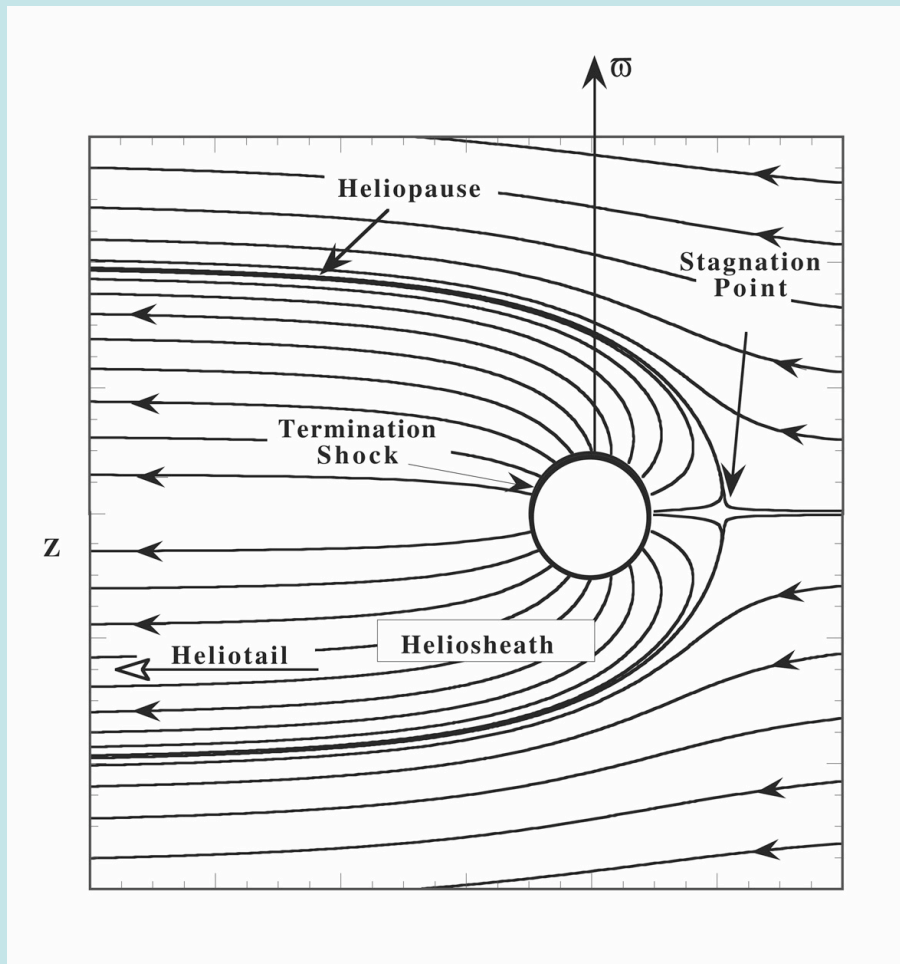
Parameters:

$V_{SW} = 400$ km/s $= v_1$

Strong shock - 4:1 compression ratio so that

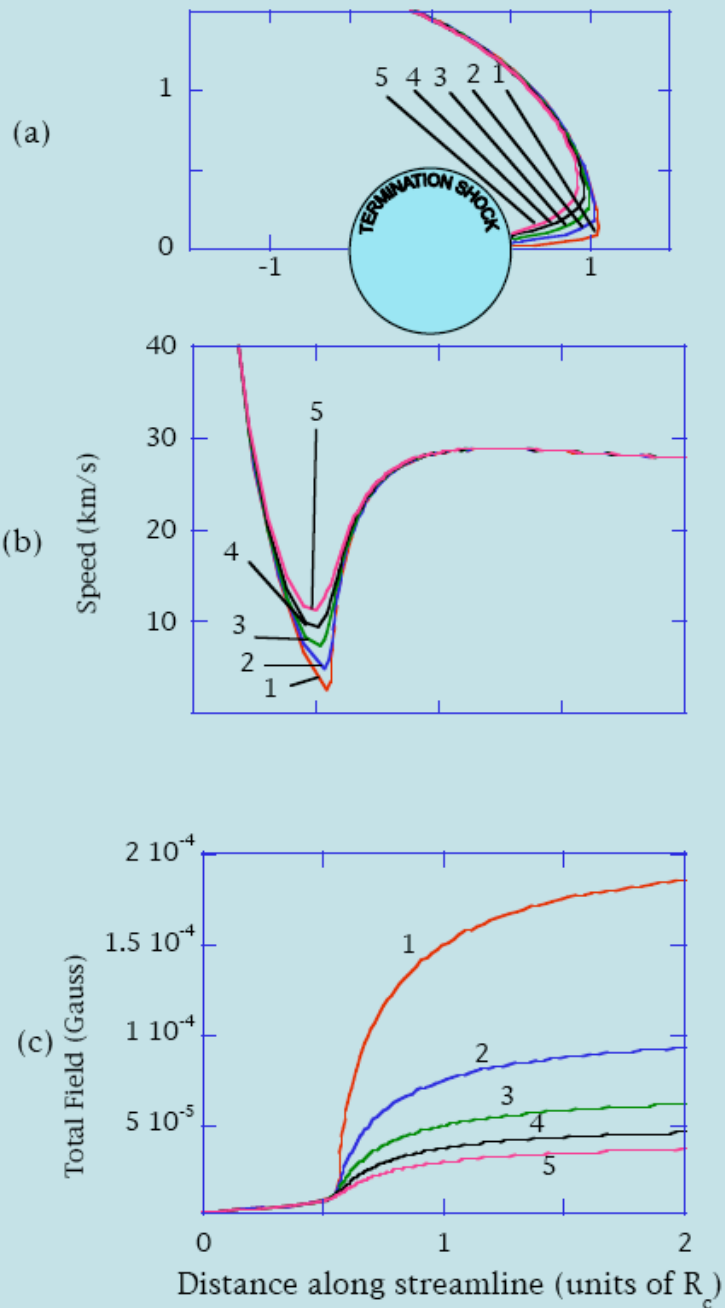$$v_2 = 100 \text{ km/s}$$

$v_{i\infty} = 25$ km/s

$r_{TS} / r_{Stagnation Point} \sim 0.5$

Suess & Nerney, Flow downstream of the heliospheric termination shock: 1. Irrotational flow, *JGR, 95*, 6403, 1990; *JGR, 96*, 1883, 1991.

Parker, *Interplanetary Dynamical Processes*, ch. IX, 1963.

Development of the 'magnetic wall':

1)   Potential flow model (Parker, 1963) of incompressible flow in the heliosheath.

2) Kinetic advection of the Parker spiral magnetic field.

<u>The plots on the left show the result in the Y-Z plane.</u>

(in the X-Z plane the polar field line undergoes no amplification because the flow is field-aligned there in the classical picture)

Nerney, S. F., and S. T. Suess, Flow downstream of the heliospheric termination shock: The magnetic field on the heliopause, *JGR, 98(A9)*, 15,169-15,176, 1993.
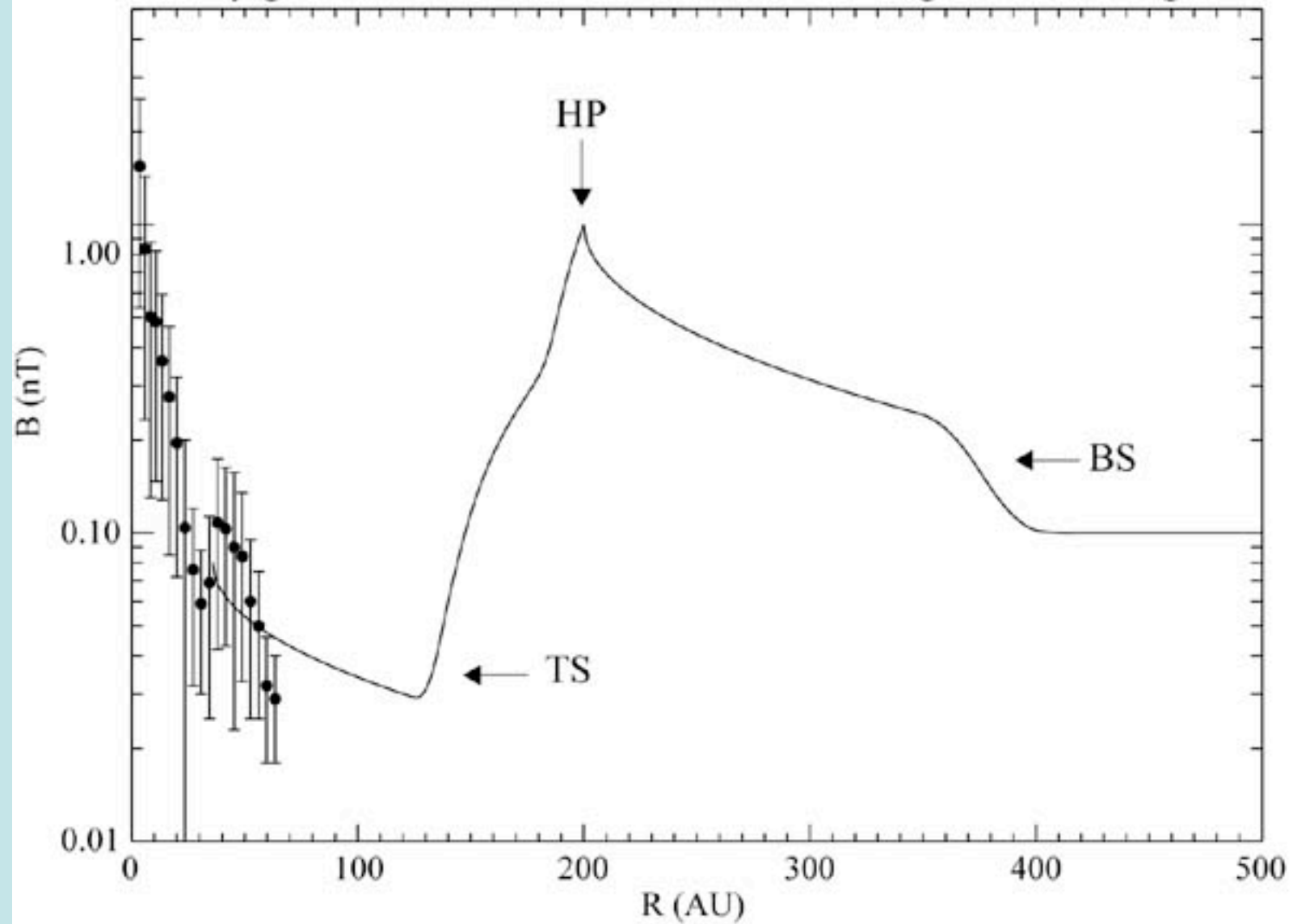
Linde, T. J., T. I. Gombosi, P. L. Roe, K. G. Powell, & Darren L. DeZeeuw, Heliosphere in the magnetized local interstellar medium: Results of a three-dimensional MHD simulation, *JGR, 103(A2)*, 1889-1904, 1998.

V⊥B
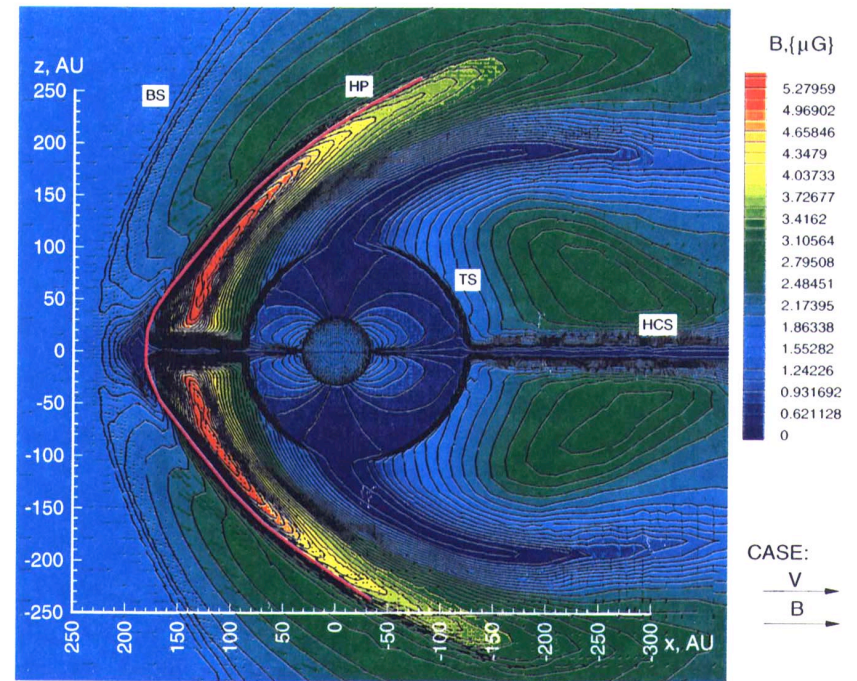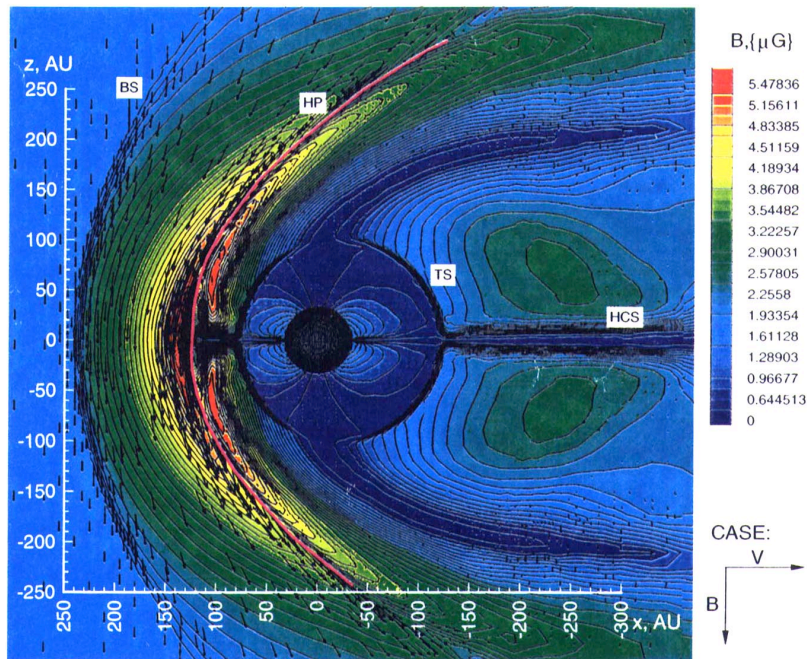
V∥B

Voyager 2 Observations and Model Prediction of Magnetic Field Strength

April 1999; G. Zank (U.Del./Bartol)
A. Szabo & L. Burlage (NASA GSFC)

The field line topology beyond the termination shock:

The plot at the right is a depiction of what the classic Parker spiral would look like for T_S=100 AU and a 400 km/s wind. This makes it hard to see anything so the following plots of the spiral in the heliosheath **assume a spiral angle at the outside boundary of the termination shock of 45º.**
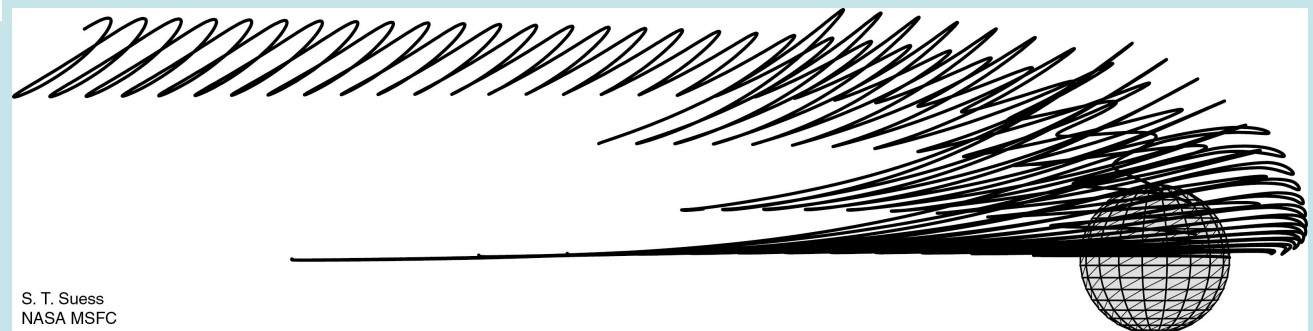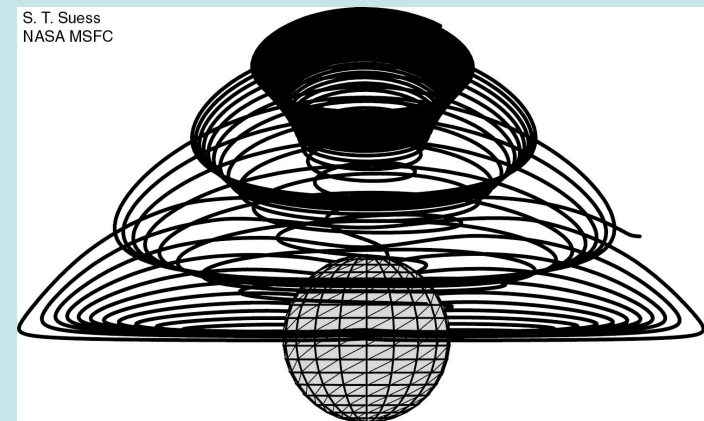
Nerney, S. F., S. T. Suess, & E. J. Schmahl, Flow downstream of the heliospheric termination shock: Magnetic field line topology and solar cycle imprint, *JGR, 100(A3)*, 3463-3471, 1995.
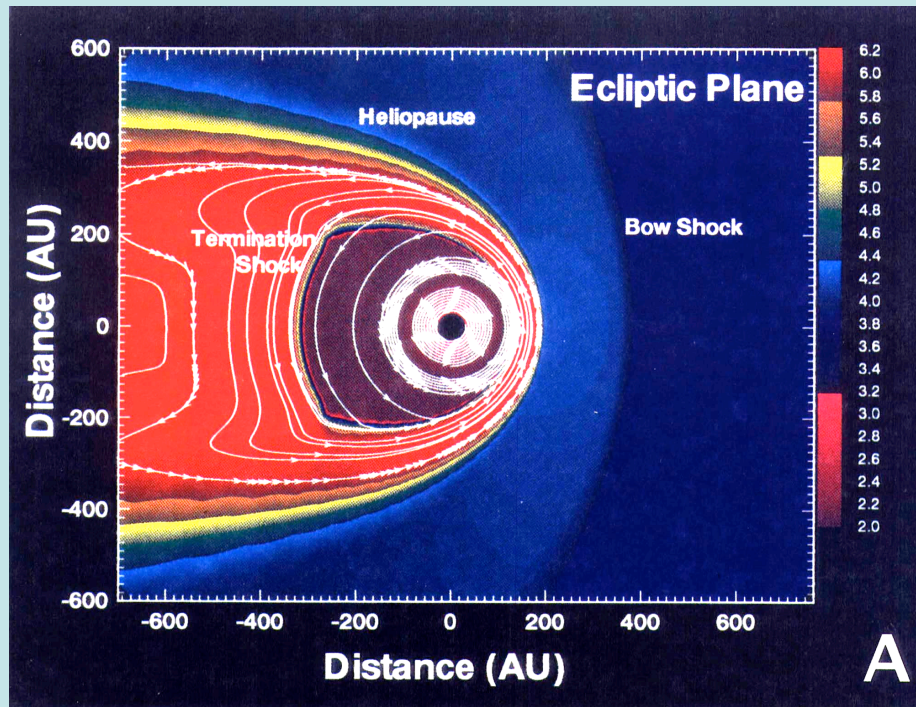
Y

X

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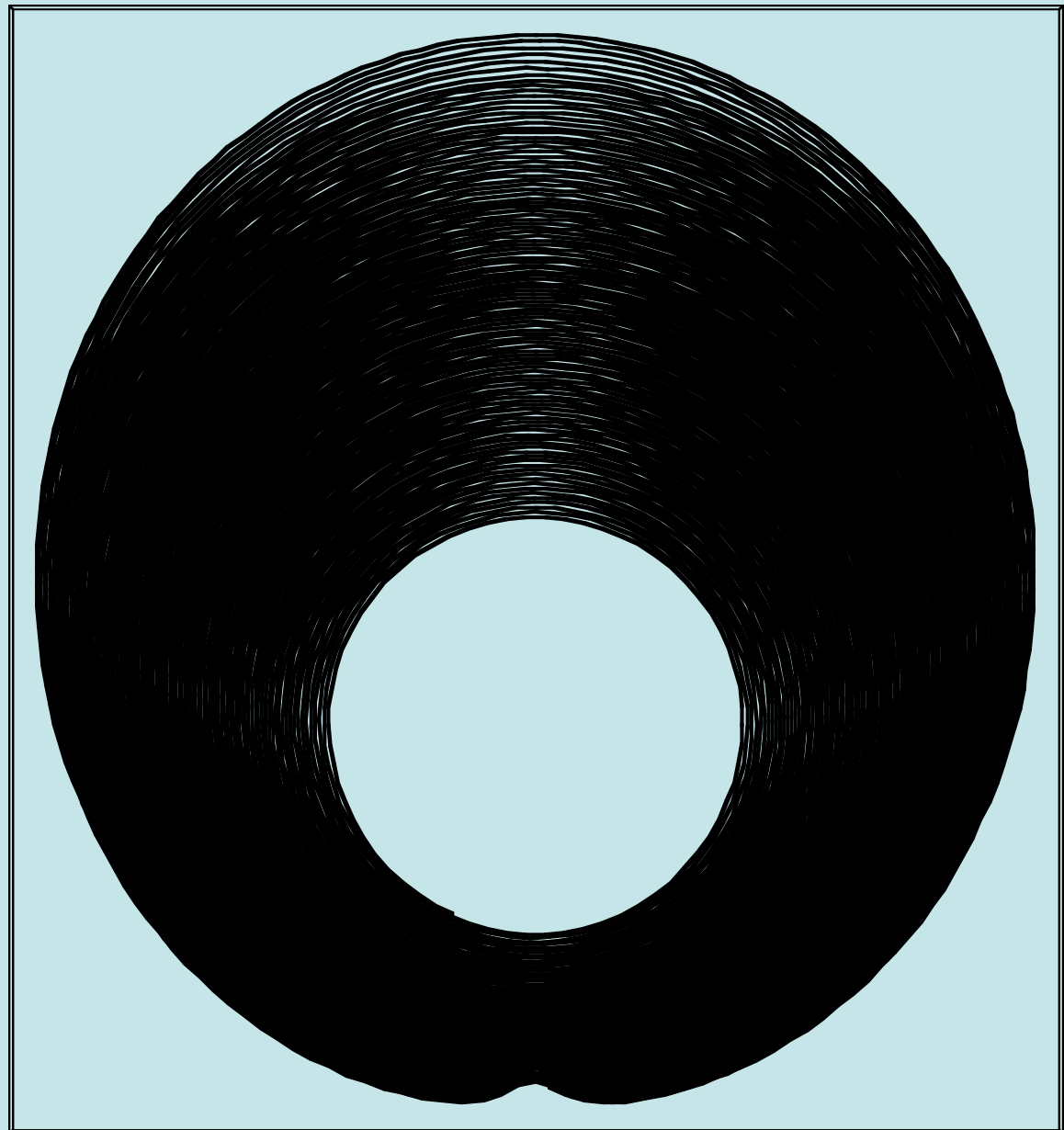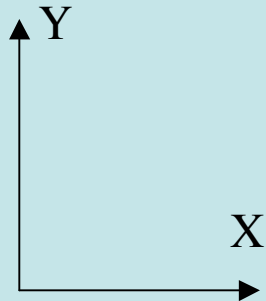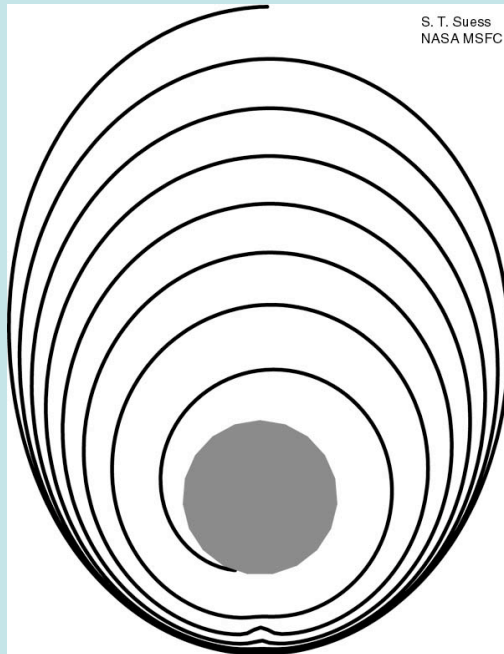
Nerney et al., *JGR, 100(A3)*, 3463-3471, 1997; also

http://science.nasa.gov/ssl/pad/solar/suess/Interstellar_Probe/IMF/IMF.html

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A: Shown in white are the Parker field lines in the ecliptic plane, in a 'kinematic field' approximation. Color is temperature. Simulation is from Pauls & Zank (*JGR, 101*, 17,081, 1996).

B: "Tornado" structure of the IMF in the polar regions.

Note that field lines can pass multiple times through the termination shock.
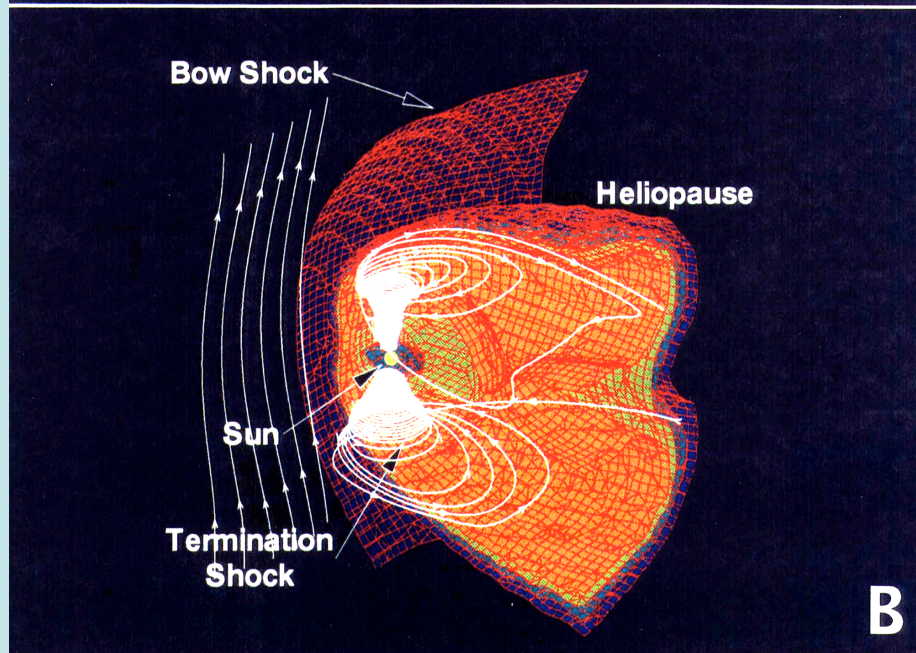
Zank, G., Interaction of the solar wind with the local interstellar medium: A theoretical perspective, *Space Sci. Rev., 89*, 413-688, 1999.

(also Pauls & Zank, unpublished)

Opher, et al., *ApJ*, 2003.

Northern Hemisphere — Voyager 1

Southern Hemisphere — Voyager 2
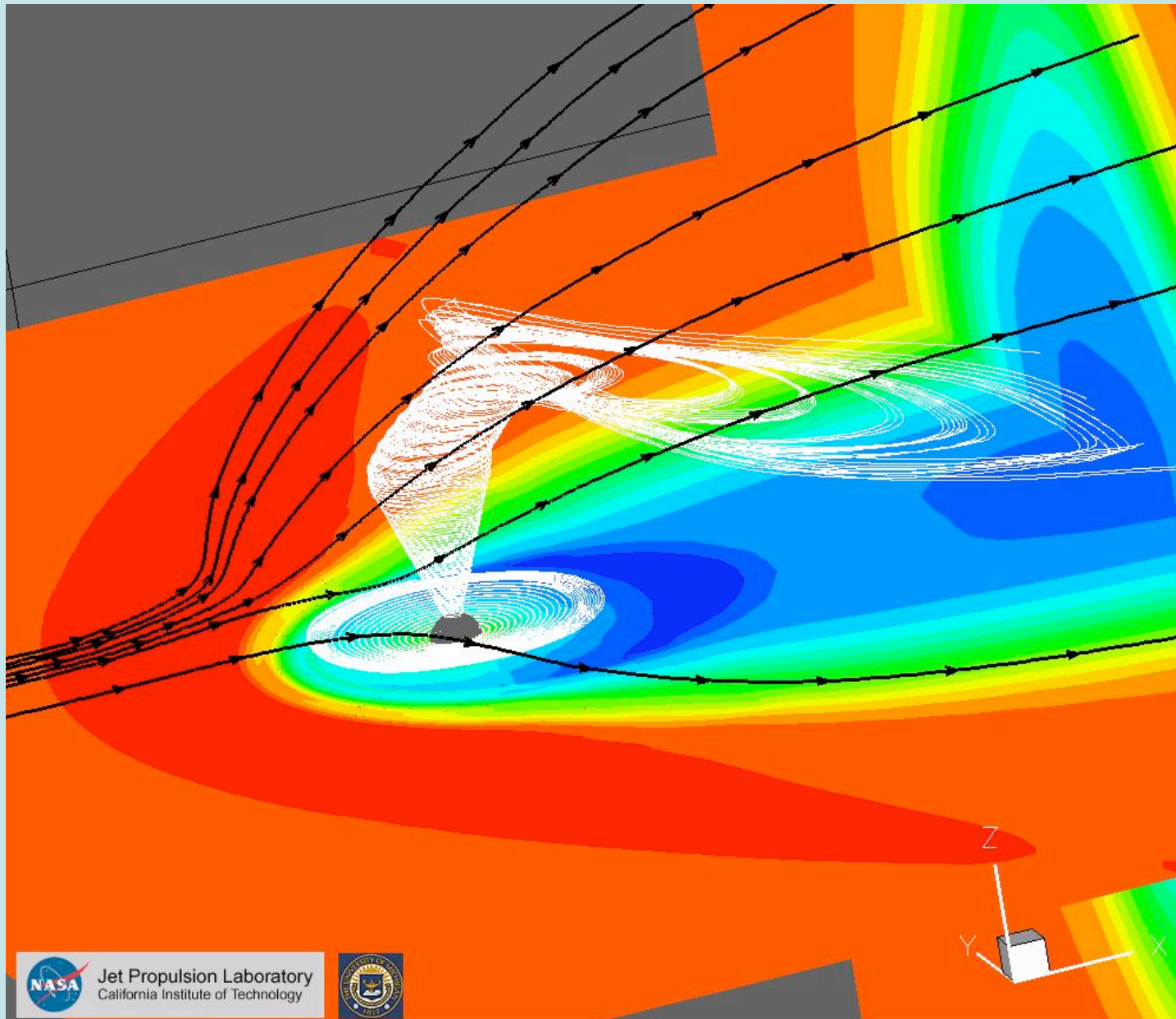
The tilted HCS is carried to the termination shock. The tilt changes systematically over the solar cycle, but this time scale is short compared to the advection time through the heliosheath.
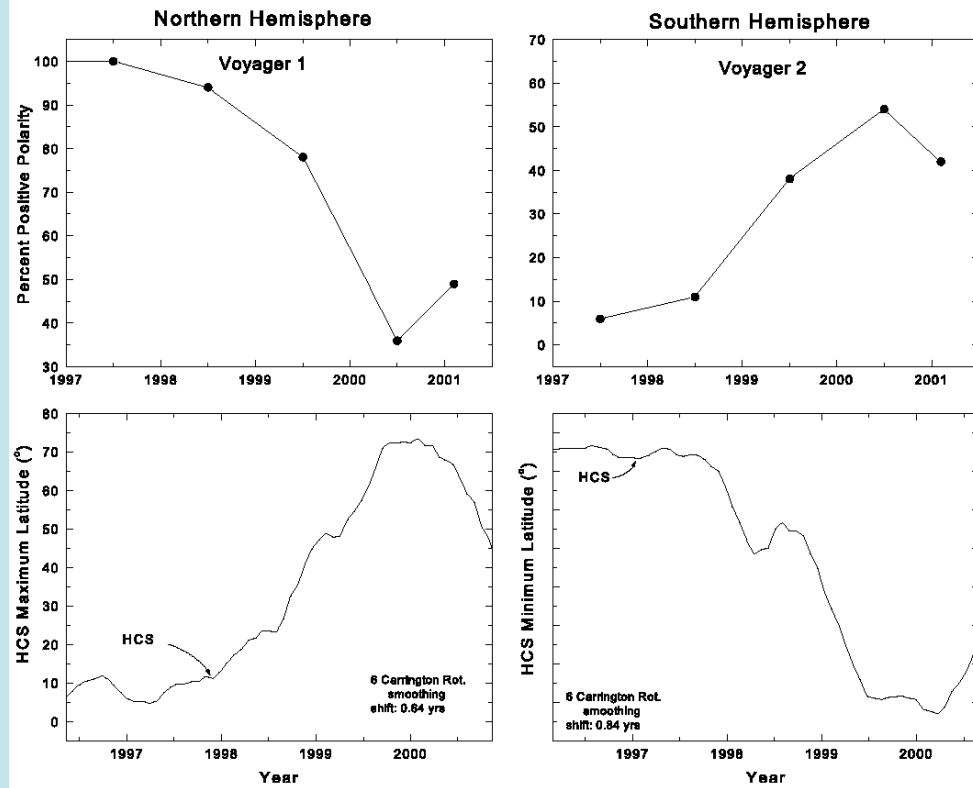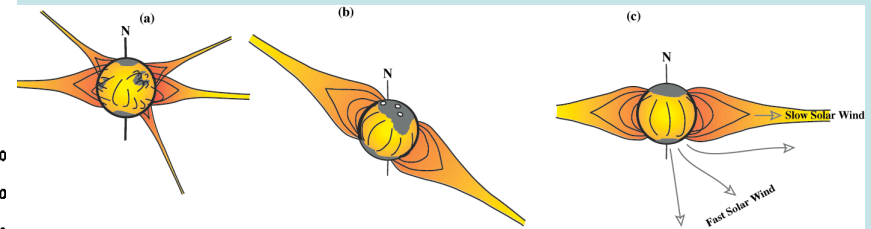
Burlaga, Ness, Wang, & Sheeley, Heliospheric magnetic field strength & polarity from 1 to 81 AU during the ascending phase of solar cycle 23, *JGR*, *107(A11)*, 2002.
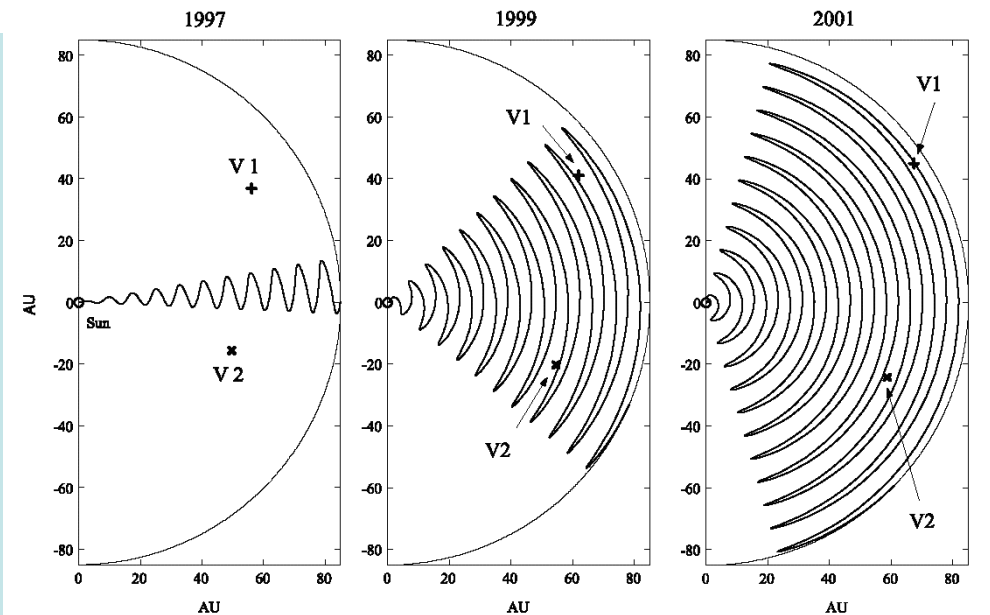
What is the imprint of the changing tilt of the HCS on the magnetic field in the heliosheath?:

Suess & Nerney
NASA MSFC

(-)

(+)

Ω_{SUN}

Termination Shock

(Strongly mixed polarity)

Suess & Nerney
NASA MSFC
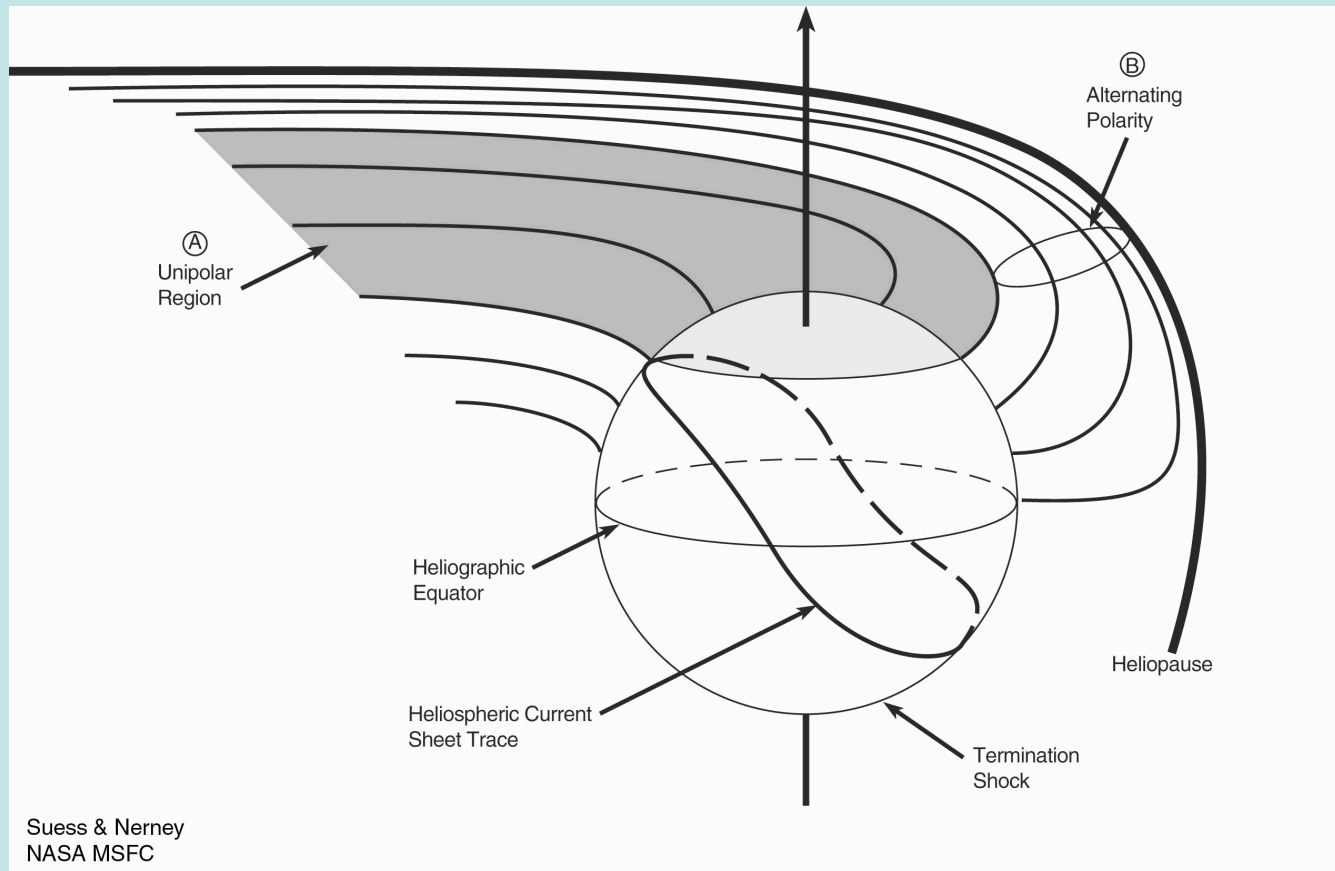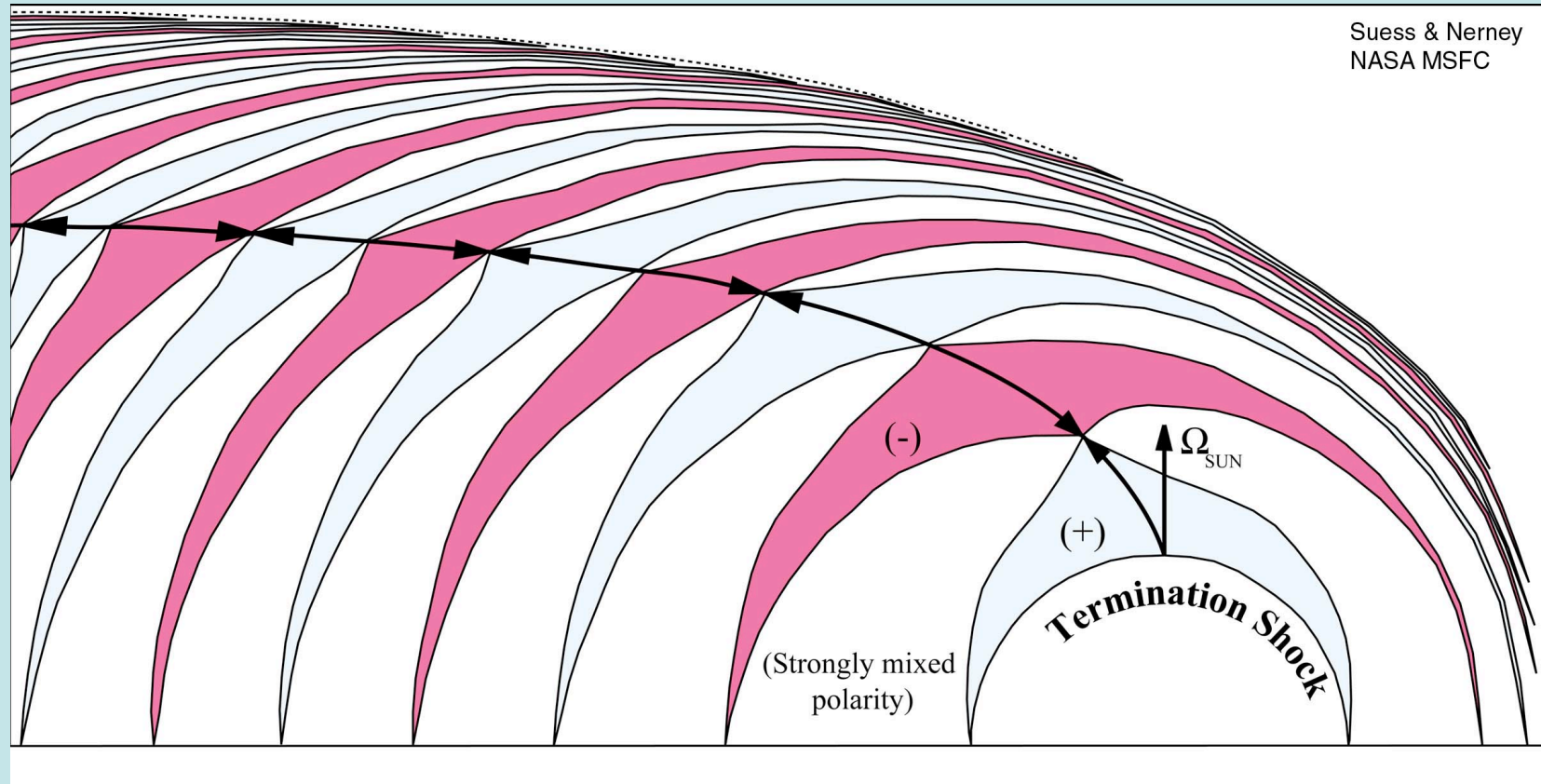
The principle conclusion is the the magnetic field in the heliosheath is of rather mixed polarity over the most of the volume and especially near the heliopause.

Cosmic rays probably gain access to heliosphere field lines fairly easily. But, the heliosheath may present a strongly scattering medium to the cosmic rays.

Nerney, Suess, & Schmahl, JGR, 1995.

Suess & Nerney
NASA MSFC

(-)

Ω_{SUN}

(+)

Termination Shock

(Strongly mixed
polarity)
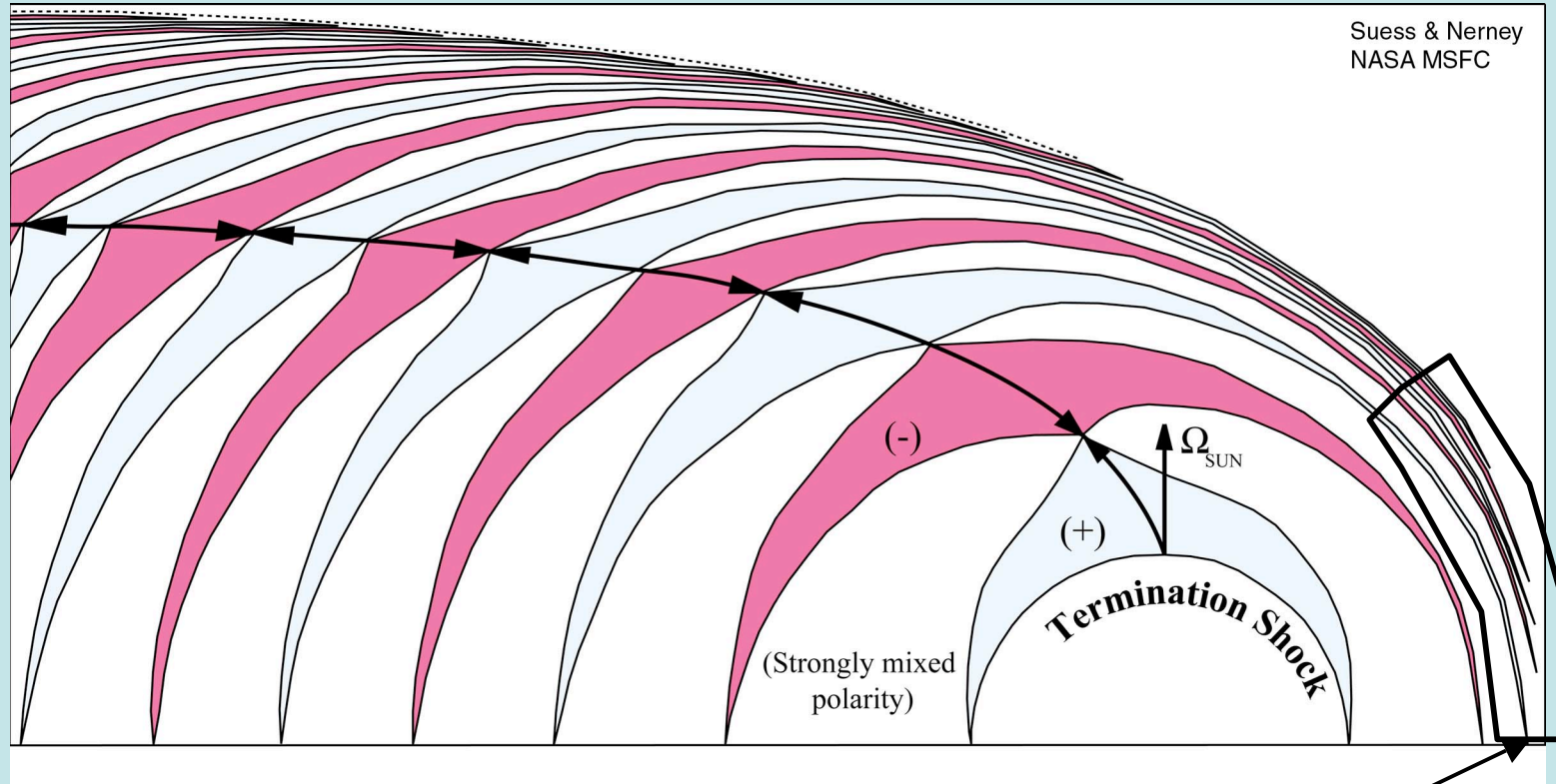
Reconnection in this region is likely because β<<1 and oppositely directed magnetic fields are being pressed together - just as at the Earth magnetopause. The region can be analyzed analytically using a 'planar approximation', transforming (r,θ,φ) coordinates to (x,y,z).

Energetic reconnection is observed to normally accelerate particles.

Modeling the magnetic field in the heliosheath (an analytic model): The irrotational / incompressible flow model is a convenient utility.

•It is essentially analytic and gives an effective O[1] flow field in the inner and outer heliosheaths when the termination shock is approximately spherical.

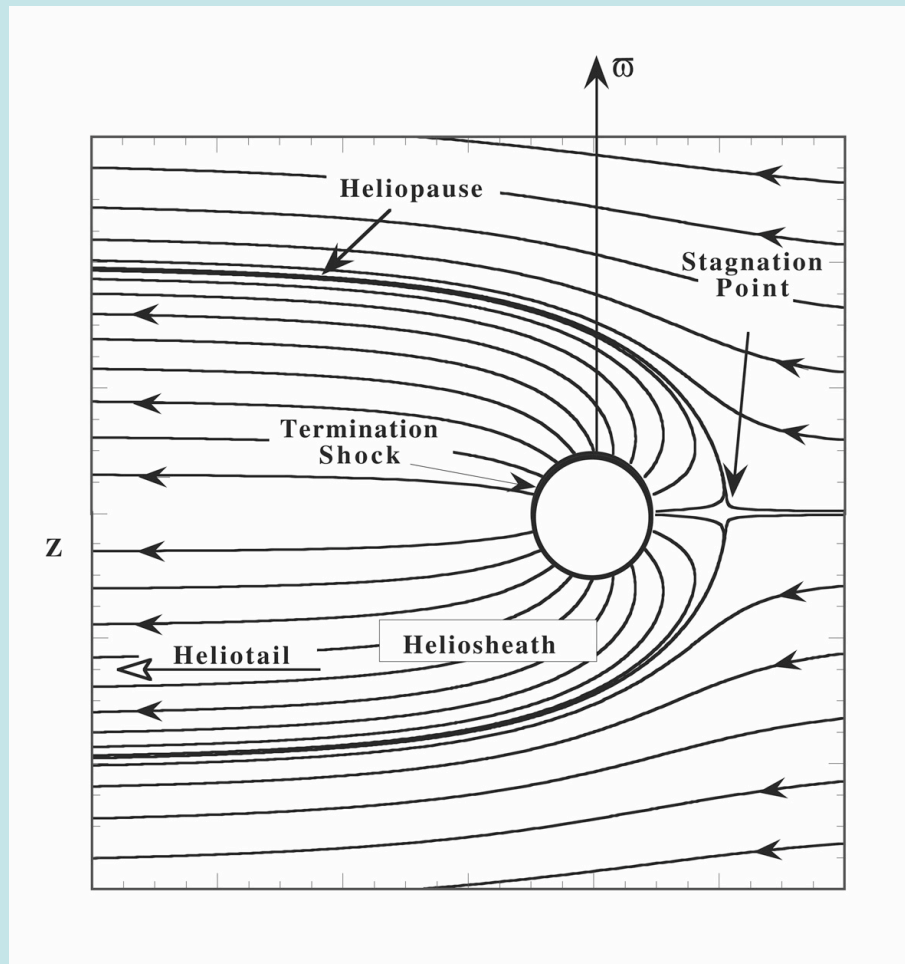•A passively advected (kinematic) magnetic field gives a good O[1] estimate of the field strength and average magnetic polarity in the inner heliosheath.

•Other irrotational flow fields can be linearly superimposed on the solution. Cranfill shows this in his dissertation for an approximation to charge exchange with interstellar neutrals in the inner heliosheath.

•The magnetic field in the *outer heliosheath* can also be estimated by imposing a kinematic field approximation.

Suess & Nerney, Flow downstream of the heliospheric termination shock: 1. Irrotational flow, *JGR, 95*, 6403, 1990; *JGR, 96*, 1883, 1991.

Parker, *Interplanetary Dynamical Processes*, ch. IX, 1963.

SUMMARY:

- Inside the termination shock:

    a) Archimedian spiral field, enhanced by charge exchange and slowing of the wind.

    b) Transverse fluctuations in the field raise the mean field strength, especially over the heliographic poles.

    c) The changing tilt of the HCS maps into the distant solar wind with little apparent alteration.

- Beyond the termination shock:

    a) The transverse component of the field is amplified by the stagnation point flow, creating the 'magnetic wall'. There is a corresponding magnetic wall in the interstellar medium immediately outside the heliopause.

    b) The IMF field lines in the heliosheath are carried into lazy loops ('magnetic tornados') up over the poles and along the flanks of the heliosphere.

    c) The imprint of solar rotation is to cause the field to reverse sign on very small spatial scales relative to the size of the heliosheath - within the region swept by the HCS.

    d) The imprint of the solar cycle is to deposit several 'unipolar' magnetic envelopes in the heliosheath relatively near the termination shock.

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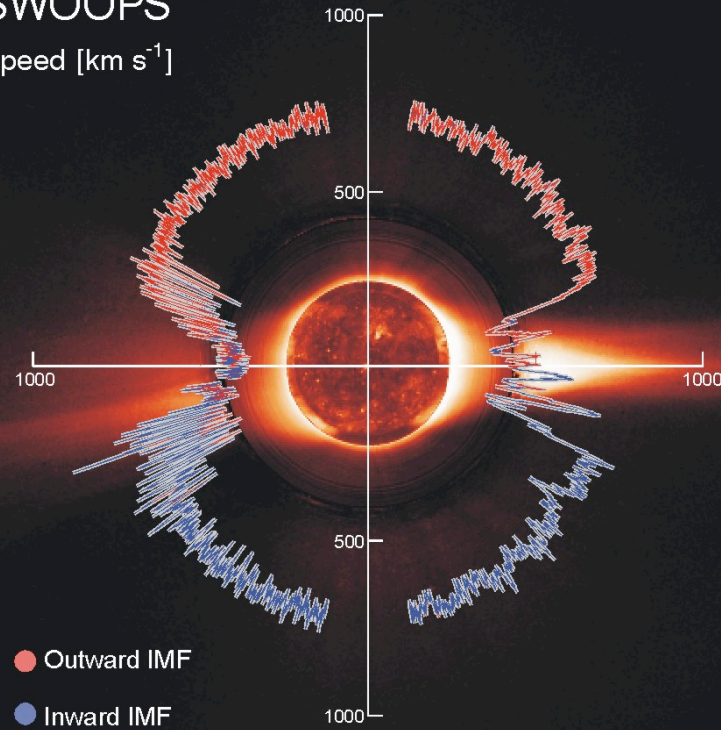
Also, some IMF pages in an Interstellar Probe web site:

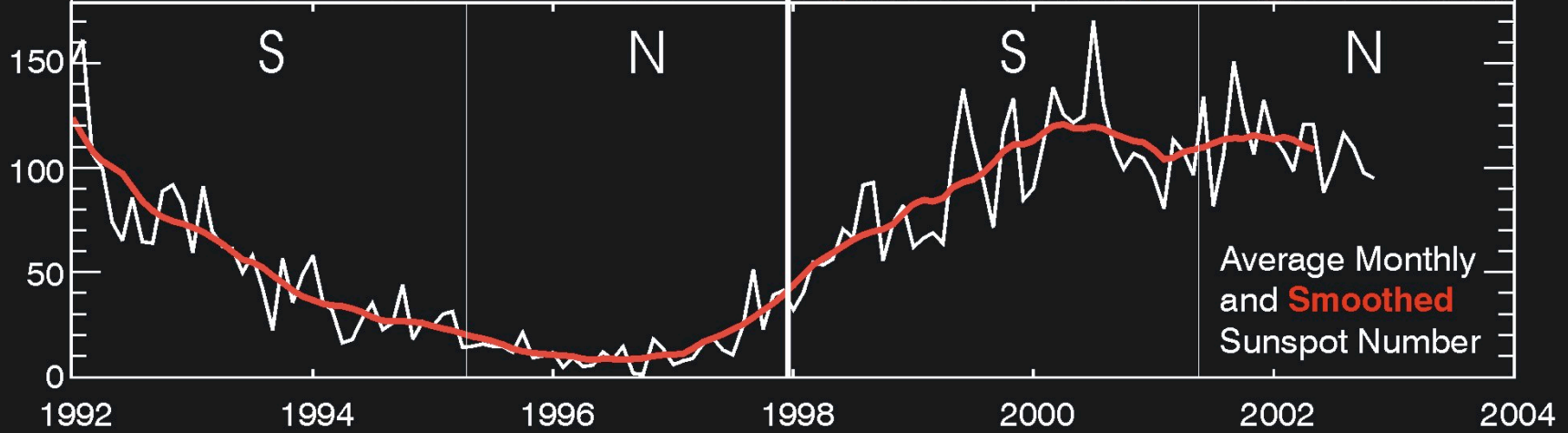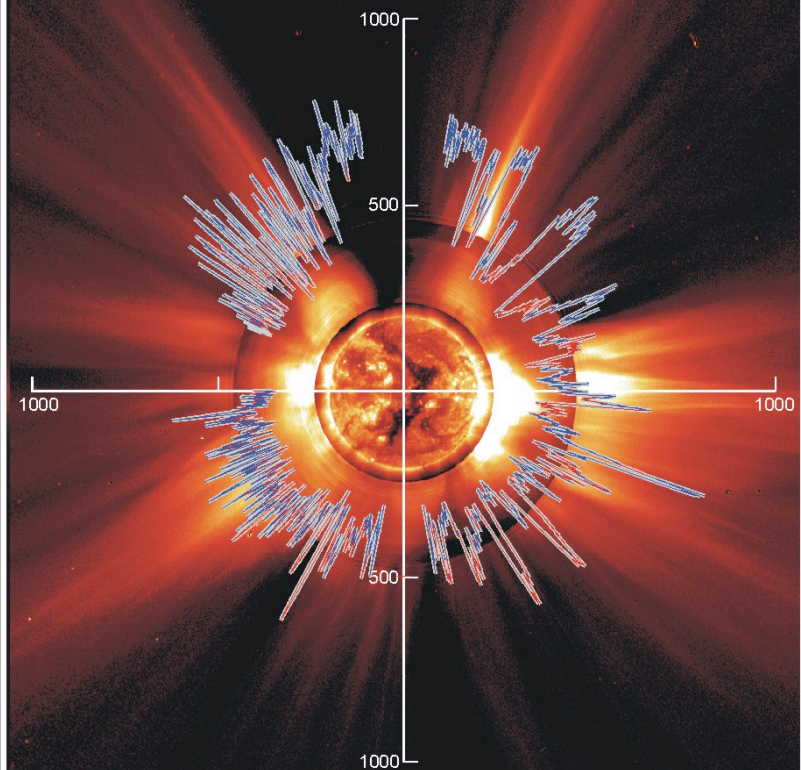http://science.nasa.gov/ssl/pad/solar/suess/Interstellar_Probe/IMF/IMF.html

Ulysses First Orbit

Ulysses Second Orbit

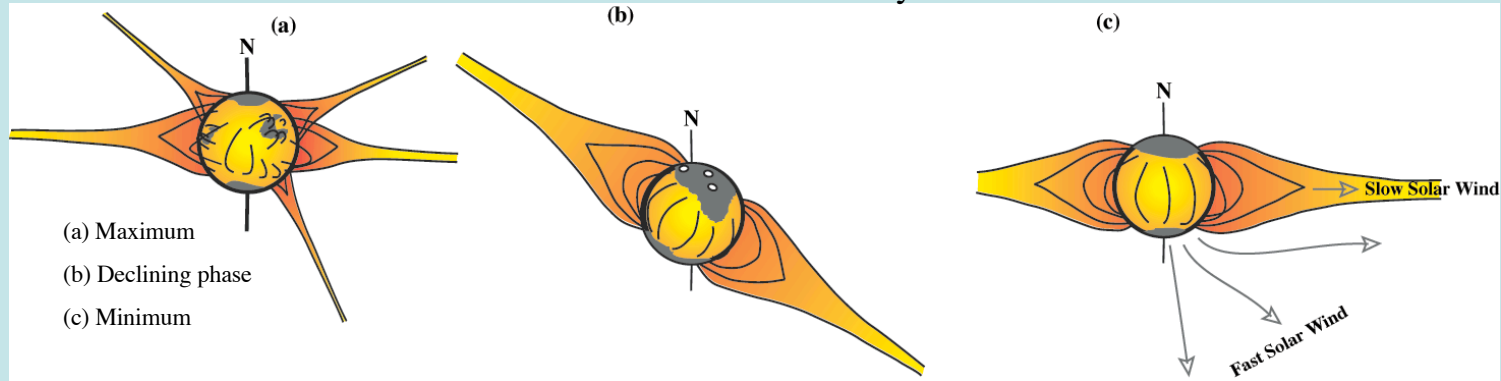SWOOPS

Speed [km s⁻¹]

● Outward IMF

● Inward IMF

Average Monthly and **Smoothed** Sunspot Number

McComas et al., *Geophys. Res. Lett.*, 2003.

TA003573R

THE SOLAR WIND: a very brief introduction

The coronal sources of the solar wind over the solar cycle

(a) Maximum

(b) Declining phase

(c) Minimum

The solar wind properties at 1 AU

$V_{SOLAR\ WIND}$ ~ 400 - 800 km/s, ~ independent of distance to O[1]
 These speeds are reached by 10-50 R_{SUN}
 The solar wind is SUPERSONIC at 1 AU
 The solar wind, to O[1], DOES NOT COROTATE WTH THE SUN

Density ~ 7 - 4 cm^{-3}, falling as r^{-2} to O[1]

Transit time to 1 AU ~ 3.5 - 2.0 days

Ulysses Solar Wind Speed Dial Plot

ULYSSES/SWOOPS
Los Alamos
Space and Atmospheric Sciences

Speed (km s⁻¹)

1000

500

1000

500

1000

ULYSSES/MAG
Imperial College
● Outward IMF
● Inward IMF

EIT (NASA/GSFC)
Mauna Loa MK3 (HAO)
LASCO C2 (NRL)

End of orbit (1998)

E

Solar Minimum

N

(a)

Slow Solar Wind

Fast Solar Wind

6 years

(b)

B

N

Beginning of
orbit (1992)

(c)

N

Solar Maximum